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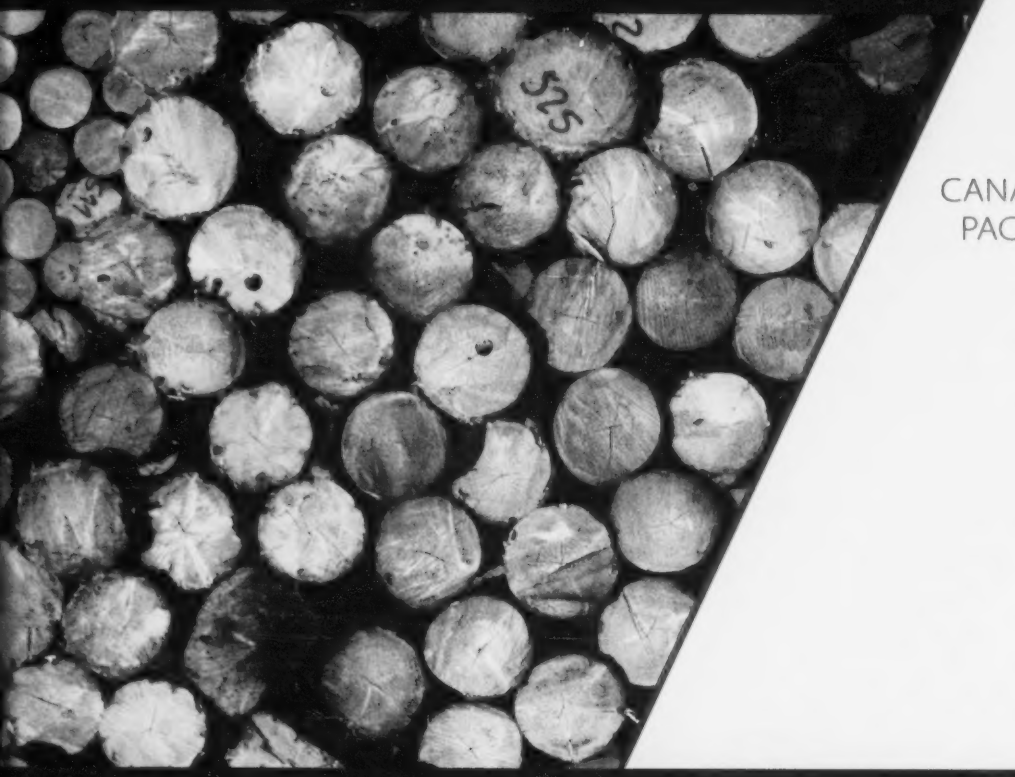

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Phytosanitary risks associated with the global movement of forest products: A commodity-based approach

Isabel Leal, Eric Allen, Leland Humble,
Shane Sela, and Adnan Uzunovic

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Phytosanitary risks associated with the global movement of forest products: A commodity-based approach

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Abstract

International trade in forest products constitutes an important component of the world's economy. Forest products may have pests associated with them that pose phytosanitary risks and could have the potential to be introduced and become established into importing countries. These risks may result in the implementation of phytosanitary requirements that could affect trade.

This report presents current knowledge of the phytosanitary threats and potential risk-reducing measures associated with the global trade in forest commodities. Commodities discussed include: round wood, sawn wood, wood chips (treated and untreated), and plant parts and live propagative materials.

As wood undergoes processing, its phytosanitary risks are generally reduced. For instance, greater phytosanitary risks are associated with international movement of round wood with bark. As bark is removed, and sawn wood is produced, the risks decrease significantly through this production process. Untreated and live forest products can present high phytosanitary risks.

This review of commodity-based phytosanitary risks associated with the global movement of forest products provides the global phytosanitary community with scientific information regarding major pests associated with forest products and recommends effective approaches to mitigate associated risks.

Résumé

Le commerce des produits forestiers représente un important secteur de l'économie mondiale. Or ces produits peuvent contenir des insectes ou organismes nuisibles qui posent un risque phytosanitaire pour les pays importateurs, notamment en se propageant au détriment des espèces indigènes. Pour parer à ce danger, les États doivent se doter de mesures de protection phytosanitaires qui peuvent avoir des incidences sur le flux des échanges commerciaux dans le secteur des produits forestiers.

Le présent rapport fait le point sur les facteurs de menace phytosanitaire et sur les moyens de parade qui pourraient être mis en œuvre pour protéger le commerce mondial des produits forestiers. Le rapport porte principalement sur les produits suivants : bois rond, bois de sciage, copeaux de bois (traités ou non traités), organes végétaux et matériel de multiplication.

Le risque phytosanitaire diminue généralement à mesure que l'on progresse dans la filière de transformation. C'est ainsi que le risque est relativement plus important pour les produits de bois rond non écorcé que pour le bois de sciage ayant subi un écorçage. Les produits forestiers vivants n'ayant subi aucun traitement présentent un risque phytosanitaire particulièrement important.

Cette étude du risque phytosanitaire posé par les produits forestiers destinés au commerce international informe utilement la communauté scientifique concernée sur les principaux insectes et organismes nuisibles associés aux produits forestiers et propose des moyens efficaces pour parer aux risques qu'ils représentent.

1. Phytosanitary Risks and Economic impact

The forest products industry is one of the world's largest resource-based industrial sectors. World trade in forest products has quadrupled over the last 30 years, and recent estimates show that it is worth approximately US $200 billion (FAO 2005a; FPAC 2005). The rapid expansion of international trade has been accompanied by an increase in the diversity of wood products and horticultural commodities traded and by an increasing spectrum of international trading partners. This trade has substantially increased the potential for spread of invasive alien pests[1] and their accompanying risk of damaging consequences for recipient countries. For example, the recent opening of trade in forest products between China, Russia and North America has led to a dramatic increase in pest introductions on both sides of the Pacific. An understanding of the phytosanitary risks associated with various types of forest commodities, and the pathways by which pests move may help to define the most efficient and effective approaches to preventing the spread of invasive organisms.

1.1 Invasive Alien Species – A Threat

An invasive alien species is a "species introduced beyond its native range that has adverse consequences for economic, environmental or human welfare" (Coluatti et al. 2006). When such a species is introduced–either accidentally or deliberately–in the absence of its predators, competitors, and pathogens, it can become established in a new territory and spread at the expense of native species. These biological invasions (bio-invasions) can affect entire forest ecosystems, with subsequent economic impacts (Liebhold et al. 1995; Dalmazzone 2000; Pimentel et al. 2005; Krcmar 2008). Particular problems occur when alien species affect native forest species. Alien pests have resulted in major changes in the composition of forests in eastern North America over the past century. For example, the introduction of chestnut blight to North America in the early 1900s and its associated impacts on the American chestnut have transformed the hardwood forests of the eastern United States and southeastern Canada. The European woodwasp, ***Sirex noctilio***, has spread widely across New Zealand, Australia, Argentina, Brazil, Chile, and South Africa, where it has caused up to 80% tree mortality in some exotic pine plantations (Hoebeke et al. 2005). An exotic invasive pest of pines of North American origin, the red turpentine beetle, ***Dendroctonus valens*** LeConte (Scolytidae), was first detected in northern China in 1998 and resulted in widespread tree mortality in 1999. This outbreak continues and has spread to three adjacent provinces, causing unprecedented tree mortality (Yan et al. 2005).

1.2 Economic Impact of Alien Species

In addition to ecological impacts, the introduction and establishment of an invasive alien species may cause significant economic repercussions for affected countries or regions. The three main areas of economic impact are:

1. Reduced value of the forest resource, for both timber and non-timber forest products. The value of the timber resource may be reduced due to loss of volume as a result of tree death or reduced growth, or a reduction in timber quality, e.g., as a result of staining, physical damage, or deformity (Pimentel et al. 1999; Krcmar-Nozic et al. 2000).

2. The costs of dealing with an established pest, including control or eradication efforts. Measures to control introduced organisms can be very costly. For example, the control of Dutch elm disease and emerald ash borer cost the provinces of Manitoba and Ontario approximately CDN $1.59 million and CDN $15.9 million each year, respectively (Coluatti et al. 2006).

3. The impact of trade disruption or phytosanitary measures, which limit the movement of goods, will depend on the policy response of trading partners to:

   - outbreaks of pests,
   - the importance of the traded commodities relative to the pests of concern,
   - the extent of the damage by the pests, and
   - the demand and supply flexibilities (FAO 2001a).

Estimates of future economic impacts of invasive species on forests are difficult to calculate, largely due to uncertainty in quantifying mortality or quality loss. Incorporating potentially important nonmarket costs is even more difficult. Finally, it is unknown how much jurisdictions are willing to spend on either eradicating or controlling new pests. There are no estimates of the economic impacts of alien species to the forest sector on a global scale. Colautti et al. (2006) list a number of alien forest pests and crudely estimate the potential loss in future export earnings for Canada at approximately CDN $10 billion. A recent analysis of the potential future economic costs resulting from a ***Sirex*** wood wasp outbreak in eastern Canada illustrates the complexity of correctly estimating the costs of any invasive species to forestry (Yemshanov et al. 2009). The often cited Pimental et al (2005) estimates losses of US $4.2 billion per year to the US forest sector from invasive forest plant pathogens and insects, as a result of reduced timber yields and increased costs of

[1] Pests are defined as any species, strain, or biotype of plant, animal, or pathogenic agent injurious to plants or plant products (ISPM No. 5, FAO 2010)

control and management. Turner et al. (2004) estimated the cumulative discounted costs to forestry of invasive insects and pathogens at between $4 and $20 billion (NZ dollars) for New Zealand over the next four decades.

The economic ramifications can be severe for nations whose forest products can potentially spread invasive organisms: trading partners may respond by curtailing the import of goods in order to prevent bio-invasion. This is often the basis for non-tariff barriers to trade, which have been shown globally to have a larger economic impact than tariffs (Sun et al. 2010). As an example, in 1993, the European Union banned imports of untreated and unseasoned sawn wood from North America to prevent introduction of pinewood nematode to Europe. Comparing the softwood sawn wood exports from Canada to western Europe in the 5-year period prior to the imposition of the pinewood nematode ban to the following 5-year period, the mean annual exports dropped by 80% (Random Lengths 1991,1996, 2001, 2006). In 1994, the year following the ban, US exports to Europe declined by US $69 million (Hicks 2001).

1.3 Alien Species Pathways

The risks associated with trade in forest products are high because pests occur on forest commodities derived from living material. Untreated wood products, including live materials (e.g., seeds and seedlings), or raw or green harvested wood products (e.g., round wood with bark, untreated sawn wood, Christmas trees, ornamental boughs), carry a particularly high risk for spread of a variety of organisms (USDA 1998; Krcmar-Nozic et al. 2000; Hicks 2001; Allen and Humble 2002; Tkacz 2001, 2002; Mireku and Simpson 2002; Moore 2005). In the case of forest products, the main phytosanitary risks are associated with pests such as insects, plant pathogenic fungi, and nematodes.

The phytosanitary risks of forest products originating from natural forests and from plantation forests (either native or exotic) are very different. Natural forests have a large number of pests compared to plantation forests, where fewer species of pests are generally present.

This review summarizes the current knowledge of the phytosanitary threats and treatments associated with the international trade of forest commodities. It focuses on untreated wood products, as these represent the highest phytosanitary risk. Information for different types of forest commodity groups is presented according to the following commodity categories:

- Round wood: with bark, debarked, and bark-free; untreated or treated by fumigation, chemical diffusion/non-pressure, or chemical pressure impregnation
- Sawn wood: with bark, debarked, and bark-free; untreated or heat-treated, treated by fumigation, chemical diffusion/non-pressure, chemical pressure impregnation, or surface treatment
- Wood chips and wood byproducts (mulch and wood waste): untreated or treated by heat, fumigation

We will also address the lack of information and research regarding the phytosanitary risks of live propagative materials (plants for planting including seeds), and plant parts (Christmas trees, decorative greenery/garlands).

For each commodity category, we describe some of the key problem organisms and discuss mitigation and treatment options available to reduce the risks they present to acceptable levels and to prevent their spread through movement by trade. It is important to note that contaminating pests[2] (sometimes referred to as "hitchhikers") have the potential to remain present or infest a commodity even after phytosanitary treatment.

Processed and modified wood such as oriented strand board (OSB), plywood, engineered wood, paper products where wood has gone through chemical processes, heat and pressure, or where wood is cut into very small particles (e.g., saw dust, wood wool, wood shavings, raw wood cut into small pieces [less than 6 mm in one dimension]), are not discussed as they present lower phytosanitary risks compared to unprocessed, green, or live products (Ridely et al. 2000; CFIA 2009a). Finished wood products, e.g., furniture, doors, and windows, are also not discussed here and represent a relatively low risk.

This review does not take into account all wood products and their associated phytosanitary risks. It does not, for instance, address solid wood-packaging materials (SWPM). SWPM have been identified as a high-risk pathway in the spread of invasive organisms, and have been the focus of recent discussions about phytosanitary measures for trade goods (Allen and Humble 2002; Cock 2003; Clarke 2004; Dubensky et al. 2001). These materials present a unique risk because they move to multiple destinations, and the wood used to create packaging materials is often of poor quality, may contain bark, and be untreated. An international standard for treatment of solid wood-packaging materials has been developed under the International Plant Protection Convention (International Standard for Phytosanitary Measures [ISPM] No.15) (FAO 2009). Although we do not address solid wood-packaging materials in this review, we acknowledge that, if untreated, they may be a significant factor in the spread of invasive non-indigenous species.

2 A pest that is carried by a commodity and, in the case of plants and plant products, does not infest those plants or plant products (ISPM No. 5, FAO 2010).

2. Global Movement of Forest Products

Worldwide trade in forest products is a multi-billion-dollar industry. In 2007, approximately 324 million m^3 (worth US$ 52.8 billion) of wood products were exported around the world. This represented an 83% increase in value and a 61% increase in quantity since 1992. Figure 1 demonstrates the increase in global trade of forest products since 1961. It is likely that some of these wood products had phytosanitary risks associated with them.

Table 1 summarizes the three top wood-exporting countries and their corresponding three main importing countries in 2007 by commodity. According to the Food and Agricultural Organization of the United Nations database (FAOSTAT 2010), Russia was the world's leading overall exporter of wood products in 2007, followed by Canada and Sweden (see http://faostat.fao.org/site/626/default.aspx#ancor). The largest importers of global wood products in quantity and value were China (US$ 51.5 billion), Japan (US$ 38.4 billion), and Finland (US$ 18.1 billion) (FAOSTAT 2010).

Data on forest-product imports and exports, such as those shown in Table 1, represent only a snapshot in time. The global trade of forest products constantly shifts, with changing political and economic conditions and fluctuating product demand. A number of new players entered the global trade of forest products in the 1990s as a result of political change. As boundaries and political structures changed in eastern Europe during that time, companies harvesting forest products for export proliferated in Russia, Estonia, and Latvia (Hicks 2001). Several countries have recently shown rapid growth in round-wood and sawn-wood exports. Export quantities of both conifer and non-conifer round wood increased by 481% in Australia, 494% in Sweden, and 386% in Russia during the 15 years between 1992 and 2007 (FAOSTAT 2010). Russia has emerged as the largest exporter of conifer round wood (Table 1). However, the Russian government recently increased export taxes on round wood by 25% to encourage domestic round-wood processing, and will increase export taxes again by 80% in 2011 (Flynn 2009). Market analysts predict that this will significantly redistribute global markets in conifer round wood and open new opportunities to other countries.

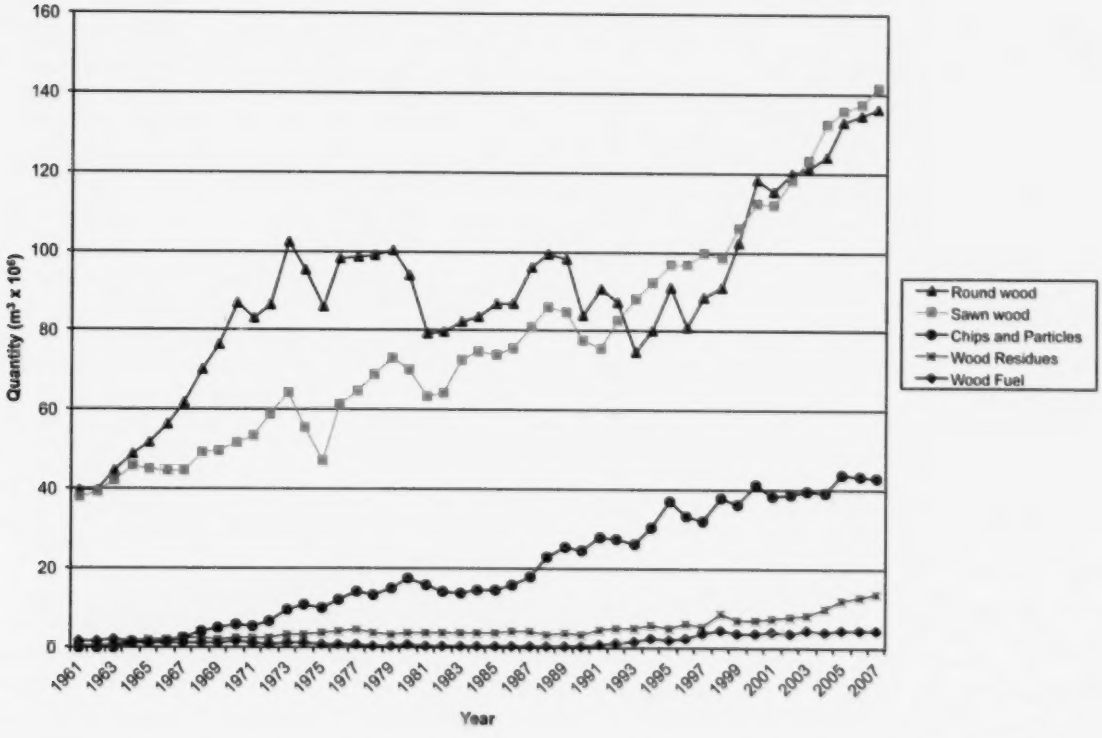

Figure 1. Export volume in cubic metres of global trade in forest products, from 1961 to 2007. (Graph derived from data taken from FAOSTAT Forestry Trade Flows site, http://faostat.fao.org/)

Table 1. Global exports of wood products in 2007 (data taken from FAOSTAT 2010).

Export Commodity	Exporting Countries	Value of Export (US$ x 10^9) (2007)	Change in Export Value Since 1992	Quantity (m^3 x 10^6) (2007)	Change in Quantity Since 1992	Importing Countries (2006)
Total Wood Products	All reporting countries	52.8	+83%	324	+61%	China, Japan, Finland
	Russia	7.5		68.4		China, Finland, Japan
	Canada	7.4		38.2		US, Japan, UK
	Sweden	4.3		16.2		Norway, Germany, Finland
Round Wood (C)	All reporting countries	7.3	+85%	82.1	+86%	Russia, US, EU (Germany, Sweden)
	Russia	3.2		35.1		China, Finland, Japan
	United States	0.87		7.6		Canada, Japan, China
	New Zealand	0.45		6.0		Korea, China, Japan
Round Wood (NC) (OTHER)	All reporting countries	3.6	+160%	35.7	+121%	China, EU (Finland, Sweden), Canada
	Russia	0.93		14.0		Finland, China, Sweden
	United States	0.82		2.3		China, Canada, Germany
	EU (France, Germany, Latvia)	0.60		4.7		Belgium, China, Austria
Round Wood (NC) (TROP)	All reporting countries	2.01	–33%	13.8	–47%	China, India, Japan
	Malaysia	0.44		4.8		China, India, Japan
	Gabon & Myanmar	0.53		3.3		China, India, France
	Papua New Guinea	0.20		2.01		China, India, Japan
Sawn Wood (C)	All reporting countries	26.6	+104%	110.1	+67%	US, Japan, EU (Italy, UK, Germany)
	Canada	6.6		32.4		US, Japan, China
	Sweden	3.9		11.3		EU (UK, Netherlands, Denmark)
	Russia	3.1		16.4		China, Uzbekistan, Japan
Sawn Wood (NC)	All reporting countries	9.1	+58%	21.5	+25%	China, Italy, US
	United States	1.4		2.8		Canada, China, Mexico
	Malaysia	0.75		2.1		Thailand, China, Philippines
	Brazil	0.67		1.7		China, Netherlands, France

(C) Coniferous: All woods derived from trees classified botanically as ***Gymnospermae***. These are often referred to as softwoods.

(NC) Non-Coniferous: All woods derived from trees classified botanically as ***Angiospermae***. These are generally referred to as hardwoods.

NC (OTHER) Non-Coniferous Other: Non-coniferous woods originating from non-tropical countries.

NC (TROP) Non-Coniferous Tropical: Non-coniferous woods originating from tropical countries.

For instance, since 1998, round-wood and sawn-wood exports to China have quadrupled (FAOSTAT 2010). In 2006, China was the world's largest importer of coniferous and non-coniferous round wood and non-coniferous sawn wood, and the largest exporter of a variety of wood commodities and finished products. Changes in the cost of round wood exported from Russia will severely impact wood-processing industries in China. This, in turn, means wide-ranging implications for global supplies of finished wood products (International Wood Markets Group Inc. 2010) and further shifts in global trade markets.

As well, reduced availability of tropical hardwood from Indonesia, in response to controls on illegal harvesting and export of species protected by the Convention on International Trade in Endangered Species (CITES), has reduced Japan's imports of Indonesian wood and veneer by more than 50% in the past decade. The response by Japan has been to import more of its tropical non-coniferous round wood from Malaysia and China, and to increase its production of coniferous plywood and other reconstituted wood-based panel products from countries such as Russia and New Zealand (Turner et al. 2007). Like China, Japan will be affected by increased costs to export wood from Russia, and the result will likely cause further changes in trade markets.

A constantly changing trade market adds to the challenge of managing phytosanitary risks. Each shift in global forest commodity markets is accompanied by changes in phytosanitary risks. Risks decrease or increase depending on the commodity traded, the country of origin, and associated factors such as the amount and frequency of trade occurring, the types of organisms present and the likelihood of their becoming established in the environment of the host country, the effectiveness and feasibility of carrying out mitigating measures, and the general willingness of the exporting and importing countries to implement the measures necessary to prevent bio-invasion.

3. Existing Practices to Prevent Entry and Introduction of Invasive Alien Species

Preventing the entry or introduction of new species is considered the most efficient and cost-effective approach to limiting the threat of bio-invasion (Dwinell 1997; Cock 2003; Tkacz 2002). Once a species is established in a new location, its control, containment and eradication can be very costly and time-consuming. A key factor is identifying and addressing key pathways for introduction of invasive alien species. Preventing introduction and spread of alien species, through risk analysis, improved interception methods, and mitigation treatments have therefore been a focus of national and international efforts.

Any measures taken by an importing country to avoid or reduce phytosanitary risks must be considered carefully, as these risks may result in considerable economic impacts both to exporting and importing countries through interrupted trade (i.e., where goods are excluded because of the presence of pests or disease, or non-compliance with required import standards). International agreements such as the World Trade Organization's Application of Sanitary and Phytosanitary Measures (WTO SPS agreement; see http://www.wto.org) and the International Plant Protection Convention have been crafted to allow countries to impose trade restrictions necessary to protect human, animal, or plant health; however, these restrictions must be supported by scientific evidence, as documented through risk assessment (FAO 2005b). The International Plant Protection Convention (IPPC; see http://www.ippc.int) is an international plant health agreement, established in 1952 with 172 current signatories, that provides an international framework for plant protection that includes developing International Standards for Phytosanitary Measures (ISPMs) for safeguarding plant resources.

Advancing technologies may ultimately lead to enhancement of prevention and reduction of risks due to forest invasive species (Chornesky et al. 2005). The more that is known about the effectiveness of particular preventive and mitigation measures, the better countries will be able to respond within the requirements of existing trade agreements. A commodity-based assessment of these measures provides additional refinement of current knowledge.

3.1 Risk Analysis

Risk analysis consists of essentially three stages: (1) pest risk assessment; (2) identification, evaluation, and selection of risk mitigation options (also referred to as the risk management stage); and (3) risk communication (Dawson 2001; Cock 2003; FAO 2007). Pest risk assessments are used to identify potential problem species, pathways of introduction, and to allow implementation of proactive prevention measures. Through this process, pest risk assessments consider the probability of importation and introduction of pests, and the probability of establishment and spread, once introduced.

The number of potentially bio-invasive species is enormous; of these, only a small proportion has been characterized in any detail (Palm 1999; Campbell 2001; Filip and Morrell 1996; Brasier 2008). Because risk from an unknown organism is real but unquantifiable, some scientists advocate a risk-analysis approach that focuses on pathways of entry

and generic groupings of pests and diseases rather than on specific organisms (Ridley et al. 2000; Cock 2003; Brasier et al. 2008). Bigsby (2001) states that a purely pest-based analytical approach, although useful for categorizing pests as quarantine or non-quarantine, may not give a measure of the overall risk associated with a commodity, and proposes a commodity-based risk analysis, whereby commodities with more types of pests will represent greater risk per unit volume.

Risk analysis provides a systematic method of strategically setting priorities for research, mitigation, and eradication efforts. However, it should explicitly acknowledge gaps in information, recognize uncertainties, and consider global, local, and regional factors.

3.2 Prevention of Introduction by Detection and Interception

Pest detection is key to preventing the entry and spread of forest invasive alien species. However, due to the large, ever-increasing volume of trade in forest products, only a small proportion of traded material can feasibly be inspected with available resources. Although investment in prevention can carry a cost (border control, quarantine services, and monitoring), non-investment may be far more costly in terms of economic impacts due to forest damage, lost trade opportunities (market restrictions), and higher management and control costs.

Given the impossibility of inspecting all imported cargo, importing countries often rely on their trade partners to take the necessary precautions to minimize risks of contamination. But according to Clarke (2004), because importing countries are unable to observe the care and effort of exporting countries, this reliance may generate less than optimal enforcement and monitoring of treatment processes on the part of exporting countries.

3.2.1 Detection and Reduction Through Existing Production Practices

One of the ways to reduce risk of spreading invasive organisms is to ensure that the commodity is "clean" prior to treatment and shipping. This includes, in the case of the wood trade, using timber grown and harvested under controlled conditions to minimize the possibility of pest infestation; e.g., wood grown in plantations where silvicultural techniques and/or pesticides can be used to reduce pest infestation (USDA 1998), or wood from healthy, balanced, natural forests. In some cases, applying visual inspection to grade the quality of timber in stands identified for harvest, round wood after

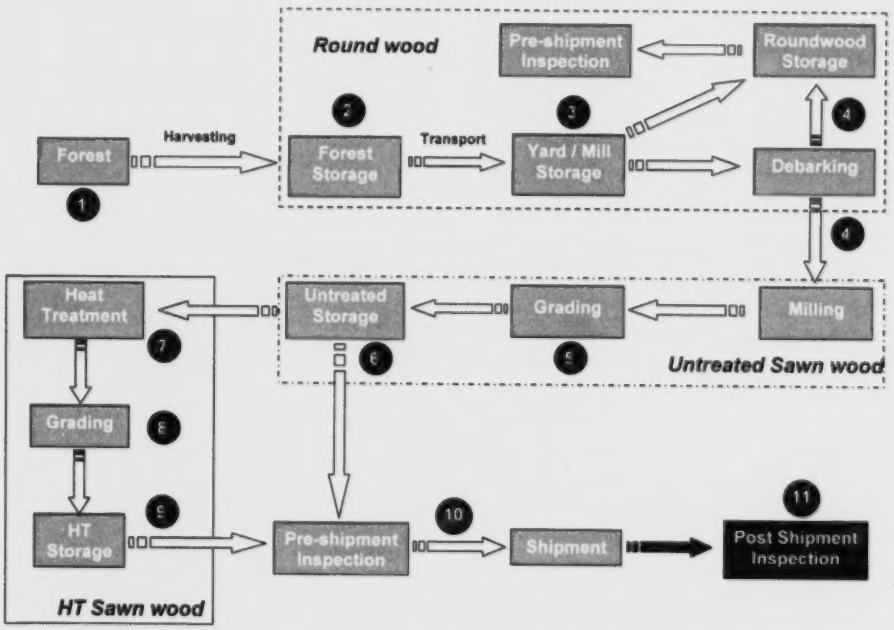

Figure 2. Generalized production pathway of round wood and sawn wood from harvest to shipment. Points within the production flow at which measures to mitigate the presence of pests and diseases in the finished commodity can be taken are identified by the numbered circles (see Table 2).

Note: this flow chart does not include chemical treatments that may be applied at different steps in the production pathway.

felling (scaling), or sawn wood after processing (grading) is carried out. These standard procedures evaluate forest-product quality.

For instance, round wood is visually evaluated after felling to determine volume and assess the impact of pests and decay. After milling, sawn wood is also visually graded; the cut wood is examined for the presence of rot and insect damage, as well as for structural defects. Higher-quality forest products are usually free of visible signs of discoloration, decay, and insect infestation. However, a limitation of visual inspection is that some pest infestations are asymptomatic and may not be detected with visual screening.

Figure 2 illustrates that, in a generalized production pathway for round wood and sawn wood, it is possible to mitigate the presence of pests and disease at various points in the pathway. Mitigation measures available for each stage in this production process are listed in Table 2. This production pathway indicates possible components of a systems approach for pest-risk detection and reduction. In some cases, the cost of implementing these mitigation activities may be substantial.

3.2.2 Phytosanitary Certification

Many countries have implemented import requirements to prevent the introduction of organisms they consider to pose phytosanitary threats. Under such requirements, a phytosanitary certificate demonstrating that phytosanitary measures have been applied to forest products being imported is often required. In accordance with the model certificate prescribed in ISPM No.12 (FAO 2001b), the certificate informs customs and plant-health inspectors on the importing end of: the trade goods, origin, and destination of the products; the party(ies) responsible; and the treatment and handling of the shipment.

Certification of products provides a level of assurance that the agreed-upon phytosanitary standards have been met for those products.

3.2.3 Detection and Inspection at Time of Arrival

Inspections are made at ports of entry to detect possible pest infestations as shipments arrive in the country. Inspection generally involves a visual screening for evidence of pest infestation.

There are significant limitations to inspection on arrival: while visual inspection can detect more advanced cases of infestation, early pest infestation is more difficult to detect. In addition, some types of infection or infestation are asymptomatic or cannot be detected without advanced techniques such as microscopy or molecular tools. As well, importing countries cannot inspect all goods coming into their ports; often only a small fraction of total volumes is inspected.

3.3 Mitigation Measures: Options for Treatment of Forest Products

Pest populations can be reduced significantly or eliminated through the implementation of mitigation measures. Section 4 details key points for mitigation treatments of different kinds of forest product commodities. Types of treatment to be used vary with commodities, and should consider tree species and physical structure, the type of commodity, and the pests of concern. For some commodity types, no options for treatment exist at this time; in these cases, controls on trade may be the only effective available alternative to reduce risk.

3.4 Mitigation Measures: Additional Care During Shipping, Handling, and Storage

Even when wood products are treated prior to transport, care is required during shipping and handling to avoid re-infection or incidental transport of contaminating organisms.

Re-infection or infestation of forest products can be avoided by various measures, including: shipping wood soon after harvesting to prevent wood from becoming infested (USDA 1998); shipping wood outside of the known period of activity of potentially contaminating organisms (see Biosecurity New Zealand [2008] for requirements for ***Arhopalus ferus*** [Mulsant]); segregating materials from potential sources of pests prior to shipping; and ensuring shipping containers and other handling conditions are kept free of organisms.

It may also be possible in the future to treat wood products in ship holds *en route;* e.g., applying heat treatment during transport (USDA 1998) or phosphine fumigation during transport (Leesch et al. 1989). For example, New Zealand currently uses phosphine to fumigate round wood in ship holds while in transit (Biosecurity New Zealand 2009). The effectiveness of *en route* treatment may vary by commodity and tree species, and also may depend on the specific conditions that exist on each vessel, as well as the expertise of the fumigators.

Some countries use timing of shipment as a measure to reduce the spread of pests, and may only import untreated round wood during winter, when pests are not active. The wood, upon being received at the port of entry, is processed and treated before the pests in the wood become active and are able to spread into the importing country's forests. For example, round wood from pine shoot beetle, ***Tomicus piniperda*** (Linnaeus), regulated areas of the Unites States may enter Canada, provided that the facility importing the round wood accepts the shipment during a period of the year when the beetle is not active and processes the round wood within a specified timeframe before the beetle becomes active (CFIA 2009b).

Limiting opportunity for potential spread of organisms when goods arrive in the importing country is also important.

Table 2. Potential mitigation measures which may be applied at each stage in the production process.

	Point in Production Chain	Measure
1	Forest or plantation: pre-harvest	Stand selected for low prevalence of pests or disease during pre-harvest evaluations, stands selected from areas known to be free from a pest of concern
2	In-forest storage of round wood	Minimize time round wood remains in forest during activity periods of pests or diseases Harvest and store when pests are not active
3	Round-wood storage in sorts or at mills	Minimize duration of storage during periods of pest activity Round wood with evidence of pest activity is removed from export production pathway during scaling Take active measures to minimize pest attack: e.g., sprinkle stored round wood with water to prevent attack, manage pest populations around storage areas (ambrosia beetle trapping)
4	Debarking	Remove bark as soon as possible after harvest to prevent post-harvest bark and woodborer attack, or to reduce existing populations of phloem-eating pests
5	Sawn-wood grading	Reduce the populations of bark and wood-boring pests and diseases by eliminating lower grades of sawn wood that have evidence of pests or disease
6	Untreated sawn-wood storage	Minimize duration of storage during periods of pest activity Manage pest populations around storage areas Take active measures to prevent contamination by pests and diseases, e.g., apply anti-sapstains
7	Heat treatment without moisture reduction (e.g., 56° C for 30 min) – with moisture reduction (KD)	Elimination of majority of deep-wood pests and diseases
8	Post-heat treatment grading	Increase quality of wood by removing defects
9	Post-heat treatment storage	Minimize duration of storage during periods of pest activity Manage pest populations around storage areas Store product in "clean" areas to prevent contamination by opportunistic organisms
10	Pre-shipment inspection	Quality control at the mill to eliminate low-quality product Phytosanitary certificate to ensure importers' phytosanitary regulations are met
11	Post-shipment inspection	National Plant Protection Organization of importing country ensures compliance with phytosanitary regulations

For example, US regulations for the import of eucalyptus chips from South America require that the chips be stored on tarmac to prevent spread of organisms into soil and water, and that trapping and surveillance systems for high-risk pests be installed around ports of entry (Crowe 2001).

3.5 Mitigation Measures: Trade Controls

In some cases, where economically feasible commodity treatments are unavailable, trade restrictions may be the only safe strategy to avoid phytosanitary hazards (Magnusson et al. 2001). Such measures have significant implications

for international trade and are managed accordingly. Under international agreements, including the World Trade Organization Sanitary and Phytosanitary (SPS) Agreement, signatory nations may set their own phytosanitary standards to control the risk of bio-invasion; however, any such measures must be supported by scientific evidence of the need for and effectiveness of the measures implemented. The International Plant Protection Convention (IPPC) sets out international standards for phytosanitary measures to facilitate trade in plants and plant products and avoid the use of unjustifiable measures as barriers to trade (FAO 1997). Free trade agreements take a similar approach.

As mentioned above, trade using solid wood packaging materials is influenced by ISPM No.15 (FAO 2009). An international standard, currently under development, will include other wood commodities.

4. Phytosanitary Risks of Forest Products Commodities

This section identifies potential phytosanitary risks associated with wood commodities and addresses the treatments that are commonly used for pest mitigation.

4.1 Pests Associated with Wood Commodities

Specific pest groups that are associated with wood will be addressed here. The organisms of primary concern are those present in trees at the time of harvest or those attacking immediately after harvest that could persist through the production chain to potentially be present in the final commodity. Of secondary consideration are those organisms that attack seasoned wood or wood in service. Many organisms growing in and on trees have no apparent negative effect on tree health or wood quality (e.g., endophytic fungi, non-pathogenic nematodes, predatory arthropods). The various organisms attacking trees may attack the bark in one part of their life history, and be found in the sapwood or heartwood at a later stage in their development or may be solely dependant on sapwood or heartwood for their nutrition. This review is restricted to those portions of trees that make up solid wood export products, therefore, pests that are associated with foliage and roots are excluded.

4.1.1 Pests Associated With the Bark

Insects

Bark beetles (Coleoptera: Curculionidae: Scolytinae [in part]) feed on the inner bark (phloem) as larvae, and at maturity pupate primarily in the bark. This group includes some of the most destructive pests of coniferous forests (Wood 1982; Paine et al. 1997) and includes a significant number of species of phytosanitary concern (primarily in the genera ***Ips*** and ***Dendroctonus***). Some species of phytosanitary concern (e.g., ***Scolytus rugulosus*** [Mueller] and ***Scolytus mali*** [Bechstein]) enter the sapwood at maturity to build their pupal chambers, penetrating as much as 1–2 cm into the wood (Solomon 1995).

The phloem-feeding habit is evident in other families of beetles. The brown spruce long-horned beetle, ***Tetropium fuscum*** (Fabricius) (Coleoptera: Cerambycidae), and the emerald ash borer, ***Agrilus planipennis*** Fairmaire (Coleoptera: Buprestidae), feed solely in the phloem as larvae and only enter the sapwood to pupate (Juutinen 1955; Poland and McCullough 2006), as do the larvae of the weevil genus ***Pissodes*** (Curculionidae: Pissodinae) (Finnegan 1958; Yoshikawa and Iwao 1987; Foit 2007).

Bark-inhabiting moths (Lepidoptera) and flies (Diptera) feed in the phloem layer and do not penetrate into the sapwood. The bark-mining habit has evolved in a number of families of moths (e.g., species of ***Marmara*** [Gracillaridae], ***Lapseyresia*** [Tortricidae: Olethreutinae]) and is associated with thinner barked portions of the trunks of immature deciduous or coniferous trees (Funk 1975; Fitzgerald and Simeone 1971). However, some species feed in the bark of mature trees (e.g., scribbly gum moths, ***Ogmagraptis*** spp. [Bucculatricidae] [Cooke and Edwards 2007]) and at least one species, the ***sequoia*** pitch moth, ***Synanthedon sequoiae*** (Hy. Edwards) (Sesiidae), can cause significant damage in larger trees (Koehler et al. 1983).

In addition to those pests that mine the phloem, a second group of pests that are present on or beneath the external bark surface are also of phytosanitary concern. Groups such as the conifer adelgids (Homoptera: Adelgidae) and various scale insects (Homoptera: Coccoidea: Diaspididae and Margarodidae) and aphids (Homoptera:Aphididae) feed on the phloem cells with piercing and sucking mouthparts (Havill and Foottit 2007; Murphy 1996; Scheurer and Binazzi 2004; Takagi 2003). As well, bark provides an oviposition substrate for species that feed on foliage of trees (some ***Lymantria*** spp. [Lepidoptera: Lymantriidae]) such as gypsy moth, pink gypsy moth, and nun moth (Pogue and Schaefer 2007).

Fungi

Fungi commonly grow in and on tree bark. Many are saprophytes and are of little or no phytosanitary consequence. Canker fungi can colonize the bark of many tree species killing portions of the bark and in some cases the whole tree (e.g., ***Cryphonectria parasitica*** [Murrill] Barr–Chestnut blight; ***Neonectria faginata*** [Lohman et al.] Castl.–Beech bark disease; ***Cryphonectria cubensis*** [Bruner] Hodges–Eucalyptus canker, and Fusarium circinatum Nirenberg & O'Donnell–pitch

canker [Sinclair and Lyon 2005]). Canker fungi can survive in untreated wood and bark chips, producing spores that could spread to natural environments (Koski and Jacobi 2004). Canker fungi are restricted to the bark and outer few centimetres of wood and, therefore, most of the infested tissue is removed during bark removal and lumber milling. Similarly, stem rust fungi do not penetrate deep into wood tissues. The relatively short-lived spores and complex life cycles of most rust fungi limit the risk of spread with bark and wood chips. Concerns have been raised, however, regarding the spread of ***Puccinia psidii*** G. Winter (guava rust) on this pathway (Glen et al. 2007; Loope and La Rosa 2008). Some fungal structures visible on bark may be the fruiting bodies of decay fungi colonizing the sapwood or heartwood.

4.1.2 Pests of Xylem (Sapwood and/or Heartwood)

Insects

The xylem-feeding habit has evolved in at least five orders of insects (Coleoptera, Diptera, Hymenoptera, Isoptera, and Lepidoptera). In the Coleoptera, the wood-boring habit is evident in many Cerambycidae (e.g., ***Monochamus***, ***Anoplophora***) (Linsley 1961; Bense 1995), some Melandryidae (Pollock 2002), the Lymexylidae (Solomon 1995), and many Buprestidae (Bright 1987; Bellamy and Nelson 2002). It is also evident in the ambrosia beetles (Curculionidae: Scolytinae: Xyleborini and Xyloterini and Platypodinae) (Wood 1982, 1993, 2007) as well as other specialized species of Curculionidae such as ***Rhyncolus*** and ***Cossonus*** (Cossoninae) and the poplar and willow borer, ***Cryptorhynchus lapathi*** (L.) (Cryptorhynchinae) (Solomon 1995). Some Diptera also feed in the xylem. The larvae of the subtropical and tropical timber flies (Pantophthalmidae) bore into the wood of living trees (Abreu and Rocha 2003; Sánchez Ramos and Reyes Castillo 2006). In the Hymenoptera, larvae of the horntails or woodwasps (Siricidae) bore deep into xylem, filling the galleries with tightly packed frass (Morgan 1968). During oviposition, females of many species introduce symbiotic fungi (required for larval development) into the wood (Slippers et al. 2003). Two other families (Anaxyelidae and Xiphydriidae) within the Hymenoptera are also referred to as woodwasps and have larvae that bore into xylem (Middlekauff 1974; Smith 1983; Kajimura 2000). Larvae of at least two families of Lepidoptera, the carpenter worms (Cossidae) and the clear-wing moths (Sesiidae), bore into the xylem (Solomon 1995).

While most of the pests of primary concern develop in stressed, dying, or recently dead trees, another group of pests preferentially attack dead, dry wood of standing or fallen timber or sawn wood. In the beetles, the larvae of most Bostrichidae are woodborers and some, such as the powder post beetles (***Lyctus***, ***Sinoxylon***, ***Trogoxylon***, and ***Heterobostrichus***) or the bamboo powderpost beetles (***Dinoderus***), are of economic importance. Adults and larvae of the wood-feeding species infest dead and dry wood, feeding on the starches in the seasoned sapwood (Loyttyniemi and Loyttyniemi 1988; Ivie 2002; Chen 2003; Choi et al. 2003; Peres Filho et al. 2006; Bajbai 2007). Many of the Anobiidae also feed in dry or seasoned wood (Philips 2002), and some cause serious damage in wood in service (Peters and Fitzgerald 1996; Blaney 1998) and furniture.

Termites (Isoptera) can be forest product pests (Greaves 1959). Gay (1969) reviewed the species of termites introduced to other regions of the world through commerce in wood products. Adventive species occur mainly in the dry-wood termites (Kalotermitidae) and subterranean termites (Rhinotermitidae). At least one species of Mastotermitidae has been introduced into new environs on infested logs (Gay 1969). Dry-wood termites (e.g., ***Cryptotermes*** spp) can tolerate low moisture conditions for lengthy periods, have small colonies, and infest timber and furniture. Small colonies can thus be transported in single small wooden articles. In contrast, damp-wood termites (e.g., ***Coptotermes*** and ***Reticulitermes*** spp.) require access to a constant source of moisture. Colonization readily occurs in timber, which has been in contact with the soil for some time prior to shipment or in ships' timbers with high moisture content. There are multiple reports of interceptions of Isoptera in log shipments (Gay 1969; Zhang and Yang 1994; Yu et al. 2002; Ferraz and Mendez-Montiel 2004; Gao et al. 2007).

Carpenter ants, ***Camponotus*** spp. (Hymenoptera: Formicidae), are one of the few pests associated with wood that do not feed on the wood itself. Many carpenter ant species excavate galleries in wood, often working along annual growth rings, in which they raise their brood. They are predators or scavengers; workers leave the nests and forage for food, returning to the nest to feed their larvae. Colonies can be constructed in downed logs (Torgerson and Bull 1995) or in standing trees, with the nests generally being excavated in the heartwood of living trees (Hölldobler 1962; Sanders 1962). Two species of ground nesting ***Camponotus*** spp., ***Camponotus compressus*** and ***C. variegatus***, have reportedly been introduced beyond their native ranges (Collingwood et al. 1997; Kirschenbaum and Grace 2008), while Wetterer and Wetterer (2004) report the possible establishment of a wood-nesting species, ***Camponotus pennsylvanicus*** (De Geer), in Bermuda.

Fungi

Many species of fungi inhabit the woody portion (xylem) of tree stems. The success, location, and extent of fungal colonization is largely governed by the nutritional requirements of the fungi, physical characteristics of the wood (e.g., chemical composition, cell structure), wood moisture, temperature, and the presence of competing organisms. Decay fungi

may be present throughout the xylem or, depending on species, may be restricted to the sapwood or heartwood. Fungi gain entry to the tree stem through wounds, branch stubs, or roots. Where fungal infections originate in the roots, columns of colonized wood may extend several metres up from the base of the tree. Most canker and rust infections of stem wood are restricted to the outer several centimetres of wood. An exception is western gall rust (***Endocronartium harknessii*** [J.P. Moore] Y. Hiratsuka) where woody galls extend to the pith (Hiratsuka and Powell 1976). Bluestain fungi, typically in the genera ***Ceratocystis, Ophiostoma, Grosmania, Leptographium,*** and ***Sphaeropsis***, colonize the moist sapwood of conifers and are generally dispersed and introduced to new hosts by insects. Some staining fungi cause surface discoloration of logs or cut lumber, but are not pathogenic to living trees (Uzunovic et al. 2008). Vascular wilt fungi (e.g., ***Ceratocystis fagacearum*** [Bretz] Hunt, ***Ophiostoma ulmi*** [Buisman] Nannf., ***O. novo-ulmi*** Brasier) are generally restricted to the sapwood. Wood decay fungi may be found in both sapwood and heartwood and, depending on the fungal species, may colonize living or dead tissues. Most wood decay fungi spread by spores produced on complex fruiting structures that form on the outside of tree stems. As these fruiting structures are generally removed during wood processing, the phytosanitary risks associated with the spread of decay fungi on wood products are relatively low. ***Heterobasidion annosum*** (Fr.) Bref. differs in that this fungus readily produces transmittable spores when infected wood is kept warm and moist (Sinclair and Lyon 2005); infested wood products could spread spores after international transport. Some decay fungi are vectored by insects (e.g., ***Amylostereum areolatum*** [Chaillet ex Fr.] Boidin), associated with Sirex spp. (Coutts and Dolezal 1969).

Nematodes

The pinewood nematode, ***Bursaphelenchus xylophilus*** (Steiner and Buhrer) Nickle, is the causal agent of pine wilt disease (Mamiya and Kiyohara 1972), and the only wood-inhabiting nematode causing serious damage to trees (McNamara 2003; Ryss et al. 2005). Larvae and adults of the nematode live primarily in living cells of the host (primarily the sapwood) and are vectored from tree to tree by species of the wood-boring beetle, ***Monochamus***. Although research has shown the possibility of non-vector transmission (Halik and Bergdahl 1994), most wood products infested by the nematode pose a relatively low risk in the absence of the insect vector.

4.2 Forest Products Commodities and Pest Mitigation Options

This section presents forest product commodities and the currently available phytosanitary treatments that are commonly used to mitigate forest pests on these commodities.

4.2.1 Round Wood and Pest Mitigation Options

International trade of untreated round wood[3] is considered a major pathway of introduction for alien invasive species that threaten the forest ecosystem of importing countries (USDA 1992, 1993, 1998; Cock 2003; Siitonen 2000; Piel et al. 2007). Round wood is roughly equal to sawn wood in volume traded on a global scale (Figure 1). Over 136 million m^3 of round wood was exported globally in 2007, a 250% increase from 1961 (FAOSTAT 2010). Round wood can be traded as full length or as a section of a tree stem. It is exported to countries as an end product (as pilings, poles, or posts) or for manufacture in the importing country.

There are four key parts to a tree stem: outer (surface) bark, inner bark (phloem), sapwood, and heartwood (Figure 3). Cambium is another part, which consists of a thin microscopic layer of nutrient cells in between phloem and sapwood, but because of its thickness it is not considered here as a layer of significance.

Each part of the tree in the form of round wood can harbour specific types of pests and thus presents different levels of phytosanitary risk. Bark, both outer and inner, provides habitat for a variety of insect pests and fungi, and the rough surface of the bark provides opportunities (crevices, hiding places) for contaminating pests or hitchhikers to be transported with shipments. Sapwood is nutrient rich and attractive to wood-boring insects, as well as to fungi and nematodes. There are some organisms that are found almost exclusively deep in the sapwood and heartwood, including decay fungi, some species of wood-boring beetles, and woodwasps. Because these are more difficult to detect and control, they can present a higher phytosanitary risk. According to Tkacz (2002), insects and pathogens that inhabit the inner bark and heartwood have a higher probability of being imported with round wood than contaminating pests, which are incidentally located on the bark surface.

Tree growth, timing of harvest, storage, and management practices can have a significant influence on the phytosanitary risk of round wood (see Section 3.2.1). For example, depending on moisture conditions, beetle-killed, fire-killed, and wind-thrown trees are more likely to have significant pest

[3] Round wood is wood not sawn longitudinally, carrying its natural rounded surface, with or without bark (ISPM No. 5, FAO 2010).

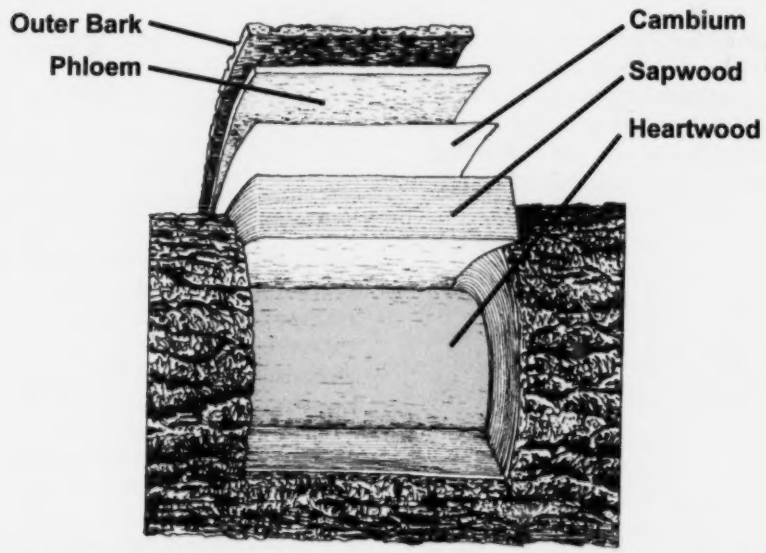

Figure 3. Parts of a tree, showing bark, sapwood, and heartwood. (Modified from: *An Introduction to Wood Anatomy Characteristics Common to Softwoods and Hardwoods* 1997. University of Kentucky, College of Agriculture)

loads than healthy trees. Damage by many bark and ambrosia beetles, woodwasps, and long-horned and metallic wood-boring beetles is often greatly facilitated when trees have been weakened due to drought (Neumann 1979; Rouault et al. 2006), poor soils, defoliation (Rouault et al. 2006), fire (McCullough et al. 1998; Neumann 1979), pollution, and storms (Bouget and Douelli 2004).

Effective mitigation treatments need to be designed, taking into consideration the phytosanitary status and source of round wood (whether it is freshly felled from healthy trees, or cut from infested or previously killed trees), as well as the phytosanitary risks associated with different parts of the round wood.

This section summarizes the treatments that are commonly used on round wood. Some of the treatments discussed in this section may not necessarily be used with the intent to reduce phytosanitary risks, but we examine them in that context. Treatments for round wood include mechanical bark removal, chemical treatments (liquid chemicals and fumigants), and other forms of treatment (heat treatment, microwave [MW], and radio frequency [RF] technologies).

4.2.1.1 Mechanical treatment – Bark Removal

Removal of bark from round wood and other regulated wood articles physically removes a layer of plant material in which a large number of insects and diseases can develop, as well as eliminating large areas of uneven surface that provide concealment for other organisms. Some bark may remain on round wood because of irregularities in the round wood surface (due to its non-circular cross section or to the presence of knots); this is referred to as debarked wood.[4]. Complete bark removal to produce bark-free wood[5] is a more effective phytosanitary measure than mechanical debarking, but it is difficult to achieve with mechanical debarkers. Industry estimates show that up to 3% of bark may remain on softwoods and up to 10% of bark may remain on hardwoods (Tom Searles, American Lumber Standard Committee, pers. comm.).

Mechanically debarked round wood is less likely to contain bark beetles, with the risk posed being dependant on the degree to which the bark and wood below the bark has been removed. Bark-free wood is likely to eliminate the risk of infestation of bark beetles in wood.

Although mechanical debarking does not completely remove bark from the surface of round wood, it is an effective tool for the mitigation of species that breed in bark, as it can significantly reduce populations of phloem-feeding bark beetles (Coleoptera: Scolytinae), long-horned woodborers (Cerambycidae), and metallic woodborers (Buprestidae) that attack the round wood prior to processing. It also eliminates

4 Wood that has been subjected to any process that results in the removal of bark. (Debarked wood is not necessarily bark-free wood.) (ISPM No. 5, FAO 2010)

5 Wood from which all bark, except ingrown bark around knots and bark pockets between rings of annual growth, has been removed (ISPM No. 5. FAO 2010).

the continuous substrate required for oviposition by regulated pests like woodwasps (Siricidae) and large woodborers such as ***Monochamus*** species, thereby preventing any further attack by these taxa (Cerezke 1975; Evans et al. 1996; Wu et al. 2000).

In addition to physically removing an infested layer, debarking enables detection of existing infestations of woodborers (e.g., ambrosia beetle pinholes; parental and/or larval galleries of many Scolytinae; Cerambycidae and Buprestidae engraved in the outer layers of the sapwood; grub holes of larger woodborers such as ***Monochamus*** spp. or stains on the subsurface layer [USDA 1991, 1992, 1993; Tkacz et al. 1998; Kliejunas et al. 2001; Evans 2007]). However, debarking and complete bark removal are unlikely to influence the occurrence of deep wood borers, some fungal organisms, or wood-inhabiting nematodes. In some instances, squaring of round wood could be considered a phytosanitary treatment in that it eliminates all of the phloem-feeding taxa and may eliminate wood boring species that only utilize the outer sap wood (e.g., brown spruce longhorn beetle).

The residual bark remaining on round wood after treatment may be subject to insect re-infestation. In a recent study, Cerambycidae and Scolytinae (ambrosia beetles and bark beetles) readily infested and developed in heat-treated and untreated round wood with bark (Haack and Petrice 2009). The Technical Panel on Forest Quarantine, a technical expert group that reports to the IPPC's Standards Committee on forest quarantine issues, recommended a 3-cm-wide, 50-cm^2 tolerance limit for bark patch size. This recommendation has been incorporated into the 2009 revision of ISPM No.15. Although Haack and Petrice (2009) found that bark patches smaller than 50 cm^2 can still harbour live insects, small bark patches dry relatively quickly rendering them less suitable for insect colonization, thus reducing risk.

The benefits of near or complete bark removal include:

- Elimination of most (if not all) phloem and outer bark inhabiting (non-wood-boring) insects, as well as the early life stages of some wood-boring beetles.
- Elimination of the ovipositional substrate or cues required by many wood-attacking species including Buprestidae, Cerambycidae, and Siricidae. In addition, some types of fungi (e.g., deep penetrating bluestain) associated with bark beetles cannot establish easily as they face competition from saprophytic molds.
- Reduction of cracks and crevices suitable for concealment of incidental contaminating pests.

Limitations of bark removal include:

- Wood without bark has a greater tendency to dry and potentially crack or check.
- This method of treatment is not effective against sapwood- and heartwood-inhabiting organisms already established in the round wood, e.g., woodwasps, nematodes, or incipient decay.
- While bark removal is important for reducing the risk of insect attack, it also exposes the nutrient-rich sapwood to fungal colonization (which in most cases would be mold fungi). Debarking neither mitigates decay, mold, bluestain, or other fungi that are already present, nor does it prevent their colonization. Additional mitigation measures, such as treatment with a fungicide, are necessary to reduce the risk of subsequent fungal attack (Morrell 1996; Morrell et al. 1998).

4.2.1.2 Fumigation

Fumigation[6] has been used for decades to control insects, fungi, and other potential pests in a variety of commodities. Fumigants should be non-explosive, easily dispersed, broadly efficacious, and able to rapidly penetrate the commodity being treated. The ideal fumigant should not alter the material treated (Kenaga 1957). Fumigant treatment involves using gaseous chemicals to kill a variety of plant pests found on and within wood and wood articles. Gas is introduced into a closed chamber under controlled conditions (USDA 1998). However, depending on the fumigant itself, chemical application process, commodity characteristics, concentration, temperature, and other environmental factors, this form of treatment may not be effective against the full spectrum of potential pests.

Despite their proven effectiveness, there are some limitations to the use of fumigants to reduce phytosanitary risk. Fumigants vary in their ability to penetrate deeply into the wood, and some are therefore limited to treatment against surface and shallow wood pests. For example, methyl bromide (MeBr) penetration depth may be limited to about 100 mm with penetration being greater in dry versus green wood (Cross 1991). To increase depth of penetration it is possible to insert chemicals, for example, methyl isothiocyanate (MITC), in solid or encapsulated form, into holes drilled in round wood, from which they can diffuse into surrounding wood through fumigant action (Mack 2006). This method is not suitable for round wood that is intended for subsequent processing, as the integrity of the wood is compromised. Ethane dinitrile (EDN), a new fumigant currently being developed, has greater diffusion ability through wood than MeBr and sulfuryl fluoride (SF) because it is soluble in water, and it is also effective at

[6] Defined as the treatment with a chemical agent that reaches the commodity wholly or primarily in a gaseous state (ISPM No. 5, FAO 2010).

high relative humidity and CO_2 concentrations, conditions sometimes found in decayed wood (Ren et al. 2006). Further research is needed to test its efficacy against a range of pests and for solid wood. The standard for the regulation of wood packaging material in international trade, ISPM No.15 (FAO 2009), states that the removal of bark has been found to facilitate the penetration of MeBr into the wood.

MeBr is the most widely used fumigant for phytosanitary purposes, and is the only fumigant currently accepted as a treatment for solid wood packing material (FAO 2009). This fumigant has a long history of use for treatment of round wood and other wood articles because of the chemical's high volatility, ability to penetrate most materials, and broad toxicity against a wide variety of pests. It is effective in killing beetles, moths, scale insects, and most fungi. In 1992, MeBr was listed as an ozone-depleting substance by the member countries of the Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP 1987), and an international phase-out schedule was put into place to phase out its use for treating non-quarantine pests between 2001 and 2010. Research is underway to identify effective and efficient alternatives to MeBr, and a review of the alternatives to MeBr is available (Mack 2006). Currently, the following fumigants, either alone or in combination, have been used or tested: aluminium phosphide, ethane dinitrile (cyanogen or EDN), metam sodium, methyl iodide (iodomethane or MI), MITC, phosphine, and sulfuryl fluoride (SF). Some of these fumigants have already been registered in some countries (e.g., phosphine in Canada, New Zealand, and Australia; SF in Germany, Sweden, and Australia). Research has intensified to assess these fumigants against pest organisms in round wood, and in particular to determine the optimum treatment parameters. More needs to be done to identify additional fumigants for potential use on wood. Phosphine fumigation was found to be an effective method for disinfesting pine round wood from the black pine bark beetle (***Hylastes ater*** [Paykull]) and the burnt pine longhorn beetle (***Arhopalus ferus*** [Mulsant]) at levels as low as 200 ppm for up to 10 days (Zhang et al. 2004). Fumigation treatment with SF was successful in eradicating the oak wilt fungus, ***Ceratocystis fagacearum***, from red oak round wood (Schmidt et al. 1997), and it has also been evaluated for control of many wood-destroying beetles (Williams and Sprenkel 1990; Soma et al. 1996, 1997; Mizobuti et al. 1996; Barak et al. 2006). More recently, SF has been reported to be an effective quarantine treatment for emerald ash borer (Coleoptera: Buprestidae) in ash round wood (Barak et al. 2010), and for ***Chlorophorus annularis*** Fairmaire (Coleoptera: Cerambycidae) in Chinese bamboo poles under commercial fumigation conditions (Yu et al. 2010).

Schmidt and Amburgey (1997) have tested methyl iodide as an alternative to MeBr for fumigation of wood pathogens in round wood. This fumigant was found to be effective for disinfesting imported round wood from nine species of forest insect pests (Naito et al. 2003), and it was also shown to be an effective treatment for the pinewood nematode and longhorned beetles infesting red pine round wood (Soma et al. 2006). However, its use may be limited because it may be difficult and expensive to acquire and use (Mack 2006).

Fumigation with combinations of gases can overcome some of the limitations evident with individual fumigants. For example, the following gas mixtures have shown promise: MeBr for egg stages and sulfuryl fluoride for larval and pupal stages of wood-boring insects (Dwinell 2001b); sulfuryl fluoride and phosphine for treatment of wood borers, bark beetles, and ambrosia beetles (Dwinell 2001b); and the combination of sulfuryl fluoride and methyl isothiocyanate for cerambycid species at moderate temperatures (Soma et al. 2004).

The effect of fumigation is short-lived. For example, if the moisture content of fumigated wood remains high, ambrosia beetles, sapstain fungi, and mold may colonize the wood at a later date (Dwinell 2001b; L. Humble, Canadian Forest Service, Victoria, BC, unpublished data). In addition, the use of fumigants can be costly and requires considerable care to minimize their release to the environment.

4.2.1.3 Liquid Chemical Treatments

Historically, various chemicals have been used in wood protection and preservation to reduce wood discoloration, to improve marketability, and to extend the wood's service life. Chemicals can be applied without pressure or with pressure.

Non-pressurized chemical treatments are applied at ambient pressure by dipping-diffusion (e.g., anti-sapstain dips or sprays, borates, and creosote). They are used for sapstain control and are applied to round wood used for log structures and post and beam construction. This treatment results in limited penetration into the sapwood. Depth of penetration varies, depending on wood species and the characteristics of the chemical treatment. Debarking wood increases penetration into the sapwood. Sometimes heat is used to increase chemical penetration. Dip-diffusion of sodium borate was not effective for eliminating pinewood nematodes or pine sawyers in debarked pine round wood (Dwinell 1996), possibly due to insufficient chemical loading or duration of exposure. In earlier studies, borate loadings of 0.42% and 1.55% boric acid equivalent (BAE) were shown to cause mortality of pinewood nematode (Smith 1992).

Chemical pressure impregnation[7] involves applying a preservative using vacuum/pressure and/or thermal processes to force the chemical deeper into the wood, which increases the extent of absorption into wood, particularly in debarked wood (Morrell 2001b). Some of the advantages to using chemical pressure impregnation treatments, compared to sprays and dip treatments, are that the quality and uniformity of the treatment are superior, there is a thicker barrier for wood-boring insects to travel through while emerging from the wood, and the surface coating also prevents future reinfestations (Morrell 2001b). Additionally, the preservatives penetrate insect galleries exposed in sawn wood (Schauwecker 2006; Schauwecker and Morrell 2008). The ratio of heartwood to sapwood also affects treatment; in most species it is easier for the chemicals to penetrate sapwood, while heartwood of some species is almost impossible to penetrate (Morrell 2001b) without using a diffusion period (Morris et al. 1996). However, some pests may not be found in heartwood since, in general, it has a lower nutrient content in all tree species, a lower moisture content in many tree species, and extractives toxic to both insects and fungi in some tree species. Pressure treatments are used to apply chemicals such as alkaline copper quaternary (ACQ), copper azole (CA), and chromated copper arsenate (CCA) to round wood or timbers used to make trestle bridges, railway ties, utility poles, marine pilings, and highway guard-rail posts. ACQ and CA are also used for decking, fencing, landscaping timbers, and other residential treated wood products. Borates are used primarily for sill plates (the bottom horizontal member of a wall), but they are also used for all framing lumber and sheathing in areas with termite problems.

Most non-pressurized and many pressurized chemical treatments are minimally successful at completely killing organisms ***in situ***. This is most likely because most chemicals do not penetrate the round wood sufficiently to destroy organisms other than those residing near the surface. A combination of pressure treatment plus diffusion may be needed to achieve the required penetration. Some diffusible chemicals, borates for example, are known to diffuse into the wood when sufficient moisture is present. Infection with bluestain[8] also increases the penetration of certain preservatives into refractory woods[9] (Byrne et al. 2006). This does not mean that shallow penetrating chemical treatments are ineffective. The chemicals used and the method of application are dependent on the pests of concern, the tree species, and the length of time the treatment needs to remain effective (Morrell 2001a).The effectiveness of surface treatment depends on the amount of chemical delivered and the depth to which it penetrates (Morrell 2001a). Moisture affects uptake: thoroughly wet woods absorb less solution than dry woods, resulting in a shallower penetration and, therefore, lower effectiveness (Morrell 2001a).

In some circumstances shallow treatment envelopes of sufficiently high biocide concentration may be enough to prevent emergence of some embedded pests. This is illustrated by properly chosen sapstain control products that can effectively prevent surface discolouration by fungi already present in the wood at the time of milling. On the other hand, it has been shown that after various chemical treatments, despite no adult emergence from treated material, some insect larvae remained unaffected, as they either avoid intermittent treated pockets, or do not ingest the wood (Schauwecker 2006; Schauwecker and Morrell 2008). As most woodborers do not ingest wood during adult emergence, further research is needed to confirm the applicability of this observation to other taxa. Avoidance of treated wood has also been noted in termites (Campora and Grace 2007).

4.2.1.4 Heat Treatment Using Ovens and Kilns

Heat treatment[10] of wood to a core wood temperature of 56°C for 30 minutes is an internationally accepted standard for the treatment of wood packaging material moving in international trade (FAO 2009).

Heat treatment is an effective, broad spectrum treatment. However, this form of treatment may be less efficient at treating round wood than sawn wood due to the practical challenges and high costs involved in heating large-dimension round wood. There are few facilities in the world that will undertake these higher costs to treat round wood. Therefore, heat treatment is usually only applied to high quality round wood and for specific needs that justify the higher treatment costs (e.g., log homes).

Pests of phytosanitary concern associated with heat treatment of round wood will be largely the same as those discussed for sawn wood in section 4.2.2.3 below.

7 Defined as treatment of wood with a chemical preservative through a process of pressure in accordance with an official technical specification (ISPM No. 5, FAO 2010).

8 Dark stain in sapwood caused by several *Ophiostoma* spp. fungi.

9 Woods that are difficult to dry.

10 Defined as the process in which a commodity is heated until it reaches a minimum temperature for a minimum period of time according to an official technical specification (ISPM No. 5, FAO 2010).

4.2.1.5 Dielectric Heating: Microwave (MW) and Radio Frequency (RF) Technologies

Microwave or radio frequency treatment of wood is an alternative form of traditional heat treatment. They are both emerging technologies that can be used as an effective way of heating and drying, caused by rotation and friction of polar molecules, mainly water molecules in wood and/or in the pest itself. The use of microwaves as a treatment method involves exposing wood to electromagnetic radiation that elevates the temperature of any material containing moisture. Microwaves are radio waves between 300 MHz and 300 GHz, with the frequencies used in industrial treatments ranging from 900 MHz to 2.45 GHz (EMItech 2006). For phytosanitary applications, relatively dry wood, instead of wet wood, or totally dry wood, may be more suitable for this method. When exposed to microwaves, dry wood has low dielectric properties and remains cool, but insects in the wood, being moister than surrounding wood, are heated to lethal temperatures. However, some studies have shown that heating patterns in wood exposed to dielectric heating are quite complex. It is not always the wettest spots that attain the highest temperatures. Drier wood has been shown to reach the target temperatures faster, for example, 0.5–5 minutes compared to over 60 minutes (Fleming et al. 2003) needed for wet wood. Wood with higher moisture content requires more energy to achieve the same heating effect. Higher water content may dissipate the available heat before it reaches larvae.

Studies by EMItech (2006) have suggested that microwave treatment can be a highly versatile method of disinfesting both solid wood packaging and raw wooden materials (such as round wood) of insects and nematodes of all life-stages.

Advantages of microwave and radio frequency treatments include:

- Efficacy on wood with and without bark.
- Impacts to operators and to the environment are lower than chemical treatments such as MeBr (e.g., no residue). For instance, electromagnetic energy is completely confined within a microwave shielded chamber during treatment. Irradiated electromagnetic energy is totally converted to heat and absorbed by the wood so that there are no losses to the surrounding environment.
- Relative to conventional heat, dielectric heating allows much quicker turnover, which may present an economic advantage.
- Temperatures higher than those required for heat treatment (minimum 56 °C) can be reached and maintained inside the wood using much lower amounts of energy.

Radio frequency treatments act through the interaction of the electromagnetic energy with the interior of the wood, quickly raising the core wood temperature to lethal levels. A possible advantage of this method is that organisms within the wood can be destroyed without the wood damage that can occur during conventional heat treatments (Tubajika and Barak 2007). There is no established industrial capacity to treat round wood by radio frequency, but there are some studies that suggest that it could be a promising method for treating round wood. These studies are evaluating the use of RF for disinfestation, with the goal of formal submissions to IPPC as a universal mitigation treatment option for wood (Ron Mack, US Department of Agriculture, pers. comm.).

4.2.1.6 Biological Control

The effectiveness of biological control agents for wood treatment is limited, but these agents may complement other treatments to allow the development of integrated control measures. More than half of the registered and available fungal products (to control various plant diseases) are ***Trichoderma***-based or ***Gliocladium***-based preparations (Butt et al. 2001). Some are intended to be used in standing trees to prevent decay, or as wound paints to treat pruning wounds. However, some of these preparations have been tested to treat bluestain and sapstain fungi in wood. For example, Vanneste et al. (2002) found that using ***Trichoderma harzianum*** Rifai as a biological control was significantly better in controlling sapstain in the internal tissues of debarked round wood than a standard fungicide treatment. Using ***T. harzianum*** as an antagonist against sapstain also proved to be effective on pine round wood in the field (Gradinger et al. 2009). White-McDougall et al. (1998) reduced sapstain in laboratory and field studies by treating aspen round wood with colourless strains of ***Ophiostoma piceae*** (Munch) and ***O. pluriannulatum*** (Hedgcock H. and P. Sydow), and an albino ***O. pluriannulatum*** strain demonstrated significant reduction in the amount of sapstain in pine round wood (Held et al. 2003). Behrendt et al. (1995) showed the effectiveness of using a colourless ***Ophiostoma piliferum*** strain, marketed as Cartapip 97®, to protect conifer round wood from wild-type bluestain fungi in the laboratory and in the field. Whereas Morin et al. (2006) found that an albino strain of ***Ceratocystis resinifera*** T.C. Harr. & M.J. Wingf. was significantly more efficient than Cartapip 97® in reducing sapstain development in spruce round wood in laboratory and field trials. Bacteria and yeasts and their products are also often explored as biocontrol agents.

Despite many years of work on the control of decay fungi on wood products in service, no biocontrol technologies appear to work consistently because of the long-term nature of the requirement and the plethora of challenging organisms. Biocontrol formulations are perceived to have narrow niche-markets, narrow host range, short-term persistence, and inconsistency in field trials. Some biocontrol agents

have potential to significantly reduce some pests of concern, but further research is needed to address inconsistencies, optimize the use of the existing products, and develop new products.

4.2.1.7 Summary of Mitigation Treatment for Round Wood

Many pests can colonize and develop in round wood, especially when the wood is from recently cut trees and bark is present. Mechanical debarking is a straightforward and cost-effective means of reducing phytosanitary risk in round wood. Debarking remains a key phytosanitary risk mitigation tool, because removing most of the bark greatly reduces the probability of introducing exotic species at a relatively low cost (Morrell 1995, 1996). Phytosanitary risks from bark beetles decrease with bark removal, depending on the degree to which bark and wood below the bark has been removed. Combining debarking of wood with pressure or non-pressure treatment with chemicals can remove existing surface pests and prevent reinfestation by new pests.

The challenge in treating round wood is the need to penetrate deep into the wood to destroy organisms that may be located in the sapwood and heartwood. Organisms located deep in the wood may be relatively inaccessible to treatments and can therefore be particularly difficult to eliminate. Application of liquid chemicals does not typically penetrate deep enough to remove all established organisms. The depth of penetration of fumigants varies depending on the type of wood, the absorption of the fumigant, and the treatment conditions. Fumigants tend to penetrate only a short distance, however, and are therefore ineffective against organisms that occur deep within round wood. Debarking increases the penetration of fumigants. Chemical pressure impregnation can be more effective than non-pressurized treatments. Heat treatment is effective, but requires high inputs of energy and/or long treatment times to achieve lethal temperatures deep in the wood. Dielectric heating, especially with radio frequency radiation, shows potential for treating round wood with minimal impact to the environment.

4.2.2 Sawn Wood and Pest Mitigation Options

Sawn wood[11] comprises a major proportion of global trade in forest products. Approximately 141 million m^3 were exported globally in 2007, representing an almost four-fold increase in global trade since the 1960s (FAOSTAT 2010; see Figure 1).

Treatments to deal with the various pest species are similar to those of round wood; however, the smaller dimension of sawn wood results in a greater efficiency for many treatments (e.g., it allows the fumigant to reach a higher proportion of the wood volume).

This section summarizes the treatments that are commonly used on sawn wood. Some of the treatments discussed in this section may not necessarily be used with the intent to reduce phytosanitary risks, but we examine them in that context. Treatments for sawn wood include mechanical bark removal, moisture reduction, heat treatment, chemical treatments (liquid chemicals and fumigants), microwave, radio frequency, and other forms of treatment (such as gamma or electron beam irradiation).

4.2.2.1 Mechanical Treatment

Complete bark removal is more effective at mitigating many pests than debarking alone, but is difficult to achieve with mechanical debarking of round wood. As most sawn wood is typically produced from mechanically debarked round wood, many of the insect and fungal pests common to the outer and inner bark of the tree have already been partially mitigated (see 4.2.1.1 above). In instances where sawn wood is milled from round wood that has not been mechanically debarked, the level of mitigation will be a function of the amount of bark removed during milling. Where bark is eliminated during the milling process, organisms requiring bark for development will be removed.

In sawn wood with some bark present, the phytosanitary risks are determined by the quantity and quality of bark present. Haack and Petrice (2009) conducted a sawn wood study, and found that Cerambycidae and bark beetles laid eggs in all sizes of bark patches tested (25, 100, 250, and 1000 cm^2) after heat treatment, but did not infest control or heat-treated sawn wood boards with no bark. Cerambycidae completed development only in boards with bark patches of 1000 cm^2, whereas bark beetles completed development on patches of 100, 250, and 1000 cm^2.

Milling of sawn wood from mechanically debarked round wood further reduces the quality of residual bark by reducing the bark patch size on the milled sawn wood. Very small pieces of bark (i.e., wane) are of minimal concern for re-infestation by bark- and wood-borers. More importantly, milling of round wood also reduces the quality of the wood itself for many pest species. This is evidenced in excessively prolonged development of species of Cerambycidae (Duffy 1953) and Buprestidae (Linsley 1943; Smith 1962), and is thought to be caused by excessive desiccation of the wood after felling and seasoning as a consequence of increased rates of water loss from the sawn wood (Duffy 1953).

[11] Wood that is sawn longitudinally, with or without its natural rounded surface and with or without bark (ISPM No. 5, FAO 2010).

4.2.2.2 Moisture Reduction

There are a variety of methods by which moisture reduction can be achieved in sawn wood including air drying and kiln drying. Air drying is the drying of sawn wood by exposing it to ambient temperatures and relative humidity. The rate of drying largely depends on climatic conditions and on the air movement. Drying, if carried out promptly after the felling of trees, may protect sawn wood against primary decay, fungal stain, and attack by certain kinds of insects. Some insects (e.g., ambrosia beetles) can breed in green sawn wood, while others prefer to breed in wood with lower moisture content (Hanks et al. 1999; Iwata et al. 2007) or in seasoned, dry wood (Linsley 1961). Growth of stain and decay fungi in wood generally occurs above 20% moisture content, with moisture contents of 40–60% being required for optimal growth (Zabel and Morrell 1992). The phytosanitary risks associated with air drying depend on moisture content achieved, which itself is determined by local relative humidity and temperature during drying. However, since many decay and stain fungi, as well as some wood boring species, may survive, moisture reduction alone is not considered an effective form of phytosanitary treatment. Some species of fungi can withstand air drying (Uzunovic and Khadempour 2007), and can survive up to 10 years in wood stored at 30–40% RH (Wilcox 1973). Similarly, some insects can survive long periods of time in low -moisture wood.

Kiln drying[12] provides a means of overcoming the limitations found in air drying when sufficient heat is added, and it may occur as a normal part of commercial wood processing with the added benefit that most pests may be destroyed in the process. Kiln drying schedules vary depending on the dimensions of the sawn wood, the wood species, and its density. Some kiln drying schedules may attain a specified temperature for a specific period of time that may achieve phytosanitary goals. For example, some commercial kilns commonly operate at more than 80°C, which greatly exceeds the temperatures necessary for the destruction of most pests, provided the heating process is sufficient to penetrate the centre of each piece of wood during the treatment. Moisture levels during treatment are also critical. Most bluestain fungi will be killed at temperatures of 40–50°C when the RH is 100% (Seifert 1993). At 20–80% RH, temperatures of up to 130°C are required before some species are killed (Zimmerman and Butin 1973). The wood decay fungus ***Lenzites trabea*** (Pers.) Fr. was killed with a 3-hour treatment at 70°C in wet conditions, but required 96–120 hrs at the same temperature in dry conditions (Cartwright and Findlay 1958).

4.2.2.3 Heat Treatment

Heat has long been used to dry wood and to kill pests (e.g., insects, fungi, or nematodes) living in or on wood commodities. However, until recently there have been relatively few studies that have been conducted to identify heat treatments to kill organisms inhabiting wood. In some studies ambient kiln temperatures were monitored rather than temperatures at the core of the wood. Pinewood nematode, some fungi, and most insects of phytosanitary concern that are associated with sawn wood are partially or completely mitigated with heating wood to a core wood temperature of 56°C for 30 minutes (FAO 2009).

Fungi

There is considerable variation in the temperatures required to kill different fungal species. Most fungi grow optimally at temperatures between 0°C and 40°C (Seifert 1993). For example, Lindgren (1942) tested 11 isolates of bluestain fungi that stopped growth at temperatures between 29–39°C. Most staining fungi can tolerate somewhat higher temperatures and will stop growing at 40–50°C under conditions of high humidity (Seifert 1993). In a survey of 64 species of wood decay fungi, Humphrey and Siggers (1934) showed that 62 of the cultures stopped growth at 46°C. Some species, known as thermophilic fungi, can tolerate and grow at temperatures higher than 50°C. Jones (1973) demonstrated that the oak wilt fungus (***Ceratocystis fagacearum*** [Bretz] Hunt) was killed when logs were treated for 6 hrs at >54°C, or longer treatment times at lower temperatures. Kappenburg (1998) reported a lethal temperature for ***C. fagacearum*** of 68°C at high humidity. Chidester (1939) reported that treatment times of 75 min at 66°C or 30 min at 77°C were required to kill three decay fungi (***Lenzites sepiaria*** Fr., ***Poria incrassata*** [Berk. & M.A. Curtis] Burt, and ***Lentinus lepideus*** [Fr.] Fr.). In a more recent study, Newbill and Morrell (1991) found that all test fungi (***Peniophora*** spp., ***Stereum sanguinolentum*** [Alb. & Schwein.] Fr., ***Postia placenta*** [Fr.] M.J. Larsen & Lombard, and ***Antrodia carbonica*** [Overh.] Ryvarden & Gilb.) were killed after 75 min at 66°C. Uzunovic and Khadempour (2007) tested bluestain and saprot fungi in naturally infested and artificially inoculated wood (***Ophiostoma clavigerum*** [Robinson-Jeffrey & Davidson] Harrington, ***O. montium*** [Rumbold] Arx, ***Leptographium longiclavatum*** S.W. Lee, J.J. Kim & C. Breuil; and ***L. terebrantis*** S.J. Barras & T.J. Perry, ***Ambrosiella*** spp. Arx and Hennebert, ***Trichaptum abietinum*** [Dicks.] Ryvarden, and ***Phellinus chrysoloma*** [Fr.] Donk). They reported that all fungi in naturally infested wood were killed at or below 56°C for 30 minutes but that some fungal isolates in artificially

[12] Defined as a process in which wood is dried in a closed chamber using heat and/or humidity control to achieve a required moisture content (ISPM No.5, FAO 2010).

inoculated wood required 61°C or a 60-minute exposure to be killed. Using similar experimental methods, E. Allen (Canadian Forest Service, Victoria, BC, unpublished data) found that the following test fungi were killed at 56°C after 30 min (***Phellinus noxius*** [Corner] G.H. Cunn., ***Heterobasidion annosum*** [Fr.] Bref., ***Armillaria ostoyae*** [Romagn.] Herink, ***Gloeophyllum striatum*** [Sw.] Murrill, ***Ceratocystis fagacearum*** [Bretz] Hunt, ***Ophiostoma wageneri*** [Goheen & F.W. Cobb] T.C. Harr., ***Ceratocystis polonica*** [Siemaszko] C. Moreau, ***Leptographium wingfieldii*** M. Morelet). ***Gloeophyllum sepiarium*** (Wulfen) P. Karst., a known thermotolerant species (Chidester 1939; Kurpik and Wazny 1978), survived to 71°C. Sapwood-inhabiting fungi have been observed to be more temperature sensitive than heartwood fungi that produce special structures (e.g., chlamydospores) facilitating their survival under adverse conditions (Newbill and Morrell 1991).

Insects

Heating wood to 56°C for 30 min will kill most insect larvae and adults. For example, in an early study by Graham (1924), ***Ips pini*** Say larvae and adults were killed at 49 and 50°C respectively, and ***Chrysobothris dentipes*** Germar required treatment for an unspecified time at 52°C. Heat treatment for 1 hr at 50°C was fatal to larvae, pupae, and callow adults of ***Ips typographus*** (Annila 1969). Similar effects were observed in a forest environment where broods on sun-exposed sides of round wood were killed and shaded broods survived. Heat treatments using kiln temperatures of 60–71°C for 1 hr were shown to kill ***Monochamus*** larvae in sawn wood (Ostaff and Cech 1978). This treatment schedule was further refined to 56°C for 30 min for treatment of pinewood nematode-infested wood, and the combination has been accepted as a phytosanitary standard for both the nematode and its vectors (Smith 1991). Mushrow et al. (2004) found that wood-inhabiting ***Tetropium fuscum*** (Fabr.) larvae, pupae, and adults were killed when treated at temperatures lower than 50°C for 30 min. Some insects, such as powder-post beetles (***Lyctus*** spp.), show a higher temperature tolerance and require treatment for 30 min at 82°C (Snyder 1923). Myers et al. (2009) recently reported thermotolerance of ***Agrilus planipennis*** Fairmaire. Larvae were capable of surviving a temperature–time combination up to 60°C for 30 min in wood. Similar results were reported by McCullough et al. (2007); ***A. planipennis*** prepupae were able to survive in wood chips at 60°C for 20 min, but not 120 min. Nzokou et al. (2008) observed ***A. planipennis*** adults emerging from round wood heated to 60°C for 30 min, but not at 65°C. Sinclair and Dillon (2008) found lower temperature tolerance for ***Agrilus;*** no life stages survived treatment at 56°C for 30 min.

Pinewood Nematode

A variety of treatments for pinewood nematode have been evaluated including fumigation and heat treatment (Ostaff and Cech 1978; Kinn 1986; Smith 1991; Wang et al.1995; Soma et al. 2001; Tomminen and Nuorteva 2001; Zheng et al. 2001). Heat treatments using kiln temperatures of 60–71°C for 1 hr were shown to kill ***Monochamus*** larvae in sawn wood (Ostaff and Cech 1978). This treatment schedule was further refined in a joint European Union/North American effort to develop a heat treatment protocol for the eradication of pinewood nematode and its vectors (Smith 1991). This study showed that treatment of wood to a core temperature of 56°C for 30 min was highly effective for treatment of pinewood nematode-infested wood, based on the extrapolation of the test data at agreed statistical efficacy of 99.994% at 95% confidence. This temperature–time combination has been accepted as a phytosanitary standard for most wood pests and forms the basis for the heat treatment measure in the international wood packaging standard ISPM 15 (FAO 2009). One subsequent study (Qi et al. 2005) reported lower mortality of nematodes in wood packaging treated at 56°C for 30 min, but the experimental methods used in the study were difficult to interpret and may not have reflected operational conditions.

4.2.2.4 Fumigation

As mentioned in section 4.2.1.2, restrictions on MeBr use have increased interest in developing alternative treatments of wood. Sulfuryl fluoride has been considered as one of the better alternatives to MeBr, but research on this fumigant as well as other fumigants on sawn wood has been limited to only a few wood-inhabiting fungi (sapstain and wood decay fungi), pinewood nematode, and some insects (e.g., Asian longhorned beetle, ***Anoplophora glabripennis*** [Motschulsky] Tubajika and Barak 2006; Drinkall and Prabhakaran 2006; Barak et al. 2006). Methyl iodide was found to be effective as a treatment of pinewood nematode infesting red pine sawn wood (Soma et al. 2006). There is a need for good scientific data to support more alternative quarantine treatments, especially with pressure to reduce the use of MeBr as a quarantine treatment.

Different fumigants have different wood penetrating abilities. Some specific combinations of fumigants can increase treatment efficacy over single fumigants. For example, there is good quarantine-level efficacy when sulfuryl fluoride is used in combination with methyl isothiocyanate (Soma et al. 2004; Abe et al. 2005). Future work should include efficacy testing of fumigant mixtures against target wood decay fungi and sapstain pathogens.

Fumigant efficacies similar to those for round wood (discussed in section 4.2.1.2) can be obtained with sawn wood, with the advantage that fumigants in general may be more successful at penetrating sawn wood.

4.2.2.5 Pesticides and Liquid Chemical Preservatives

Some anti-sapstain or surface coating non-pressurized chemical treatments of sawn wood, even though they have limited penetration, are effective against many contaminating fungi. The application of these topical fungicides or insecticides by spraying, dipping, or soaking is used primarily to prevent pests from infesting kiln-dried (and likely heat-treated) sawn wood.

Chemical pressure impregnation treatment creates a thicker barrier to pests, and if accompanied by diffusion it can result in a thorough treatment (Morris et al. 1996). Sawn wood treated in this fashion may be considered of low phytosanitary risk under specific conditions.

Ponderosa pine sawn wood with active populations of ***Arhopalus productus*** (LeConte) was treated with three conventional wood preservative systems: alkaline copper quaternary compound (ACQ), disodium octaborate tetrahydrate (DOT), or Imidacloprid. Treatment with these chemicals prevented the emergence of adults. However, none of the wood preservatives investigated killed all immature insects within the wood. Larvae emerging to the surface are a significant concern since this can result in the infestation of nontreated wood products stored on or in close proximity to the treated wood (Schauwecker 2006; Schauwecker and Morrell 2008). Borate loadings of 0.42% boric acid equivalent (BAE) achieved 100% mortality of pinewood nematode in 8 weeks and 1.55% BAE achieved 100% mortality in 4 weeks (Smith 1992). These loadings are typically achieved in sawn wood by pressure treatment (Morris et al. 1996) and are commonly exceeded in treated sawn wood (American Wood Protection Association 2008; Canadian Standards Association 2008), where 1.25% BAE is required for protection against decay and ***Reticulitermes*** species, and 2.0% BAE is required for protection against ***Coptotermes*** species.

4.2.2.6 Microwave (MW) and Radio Frequency (RF)

Microwave technology can be used to treat sawn wood that is less than four inches thick. MW exposure may not be as lethal or energy-efficient for fungi as it is for insects, especially in wood with a high moisture content such as green wood (USDA 1991). Microwaves were effective against Asian longhorned beetle (***Anoplophora glabripennis***) larvae and pupae in 4-inch-thick poplar samples with relatively low levels of radiation (Fleming et al. 2003), and also against nematodes (Ambrogioni et al. 2005; Fleming et al. 2005). MW irradiation (2.45 GHz) was found to be lethal to cerambycid larvae such as the Asian longhorned beetle and the cottonwood borer beetle, ***Plectrodera scalator*** (Fabricius) (Coleoptera: Cerambycidae), in laboratory-sized wood samples (Fleming et al. 2003, 2004). However, as moisture content of wood increases, additional MW energy is required to ensure mortality of insect larvae in wood (Fleming et al. 2003). Fleming et al. (2004) reported the values to calculate the lethal microwave doses for various volumes and moisture contents of commercial sawn wood. This work suggested that microwaves may be a feasible, practical alternative for eradication of exotic wood-boring insects. Fleming et al. (2005) concluded that commercial MW treatment (2.45 GHz) of 1-inch thick red pine sawn wood infested with cerambycids or pinewood nematodes may be a feasible alternative to conventional kiln drying or MeBr fumigation for phytosanitation. Hoover et al. (2009) tested MW radiation as a heating source and reported 100% mortality of pinewood nematode (probit-9) at 56°C.

Lower frequency radio waves may also be used for wood phytosanitary treatments. Compared with MW treatment, RF can create more even heating, higher penetration in wood, and can require less energy. It could be more suitable for thick sawn wood and large-size sawn wood. The advantage of RF is that, for some types of sawn wood, this type of treatment can be less damaging to the quality of wood than conventional heating (Tubajika et al. 2007).

The effectiveness of RF treatment in the control of wood decay fungi (***Gloeophyllum trabeum*** sensu Cunningham, ***Ganoderma lucidum*** [Curtis] P. Karst., and ***Irpex lacteus*** [Fr.] Fr. and sapstain fungus [***Ceratocystis fimbriata*** Ellis & Halst.]) in red oak, poplar, and southern yellow pine was evaluated in the laboratory. The inoculated wood blocks were exposed to RF radiation in an industrial 40-kW dielectric oven at temperatures between 60 and 70°C for 2 minutes. The test fungi were recovered and re-isolated from all of the control wood blocks, but not from RF-treated wood blocks. RF treatment resulted in complete inhibition of the fungus in 98–100% of the wood samples (Tubajika et al. 2007). These authors conclude that RF can be used to eliminate certain pathogens from asymptomatic sawn wood, but moisture content is a factor in the efficacy of this treatment.

4.2.2.7 Gamma Radiation and Electron Beam Irradiation

Different types of irradiation have been assessed for their feasibility and effectiveness in reducing phytosanitary risk. These include gamma radiation and electron beams. The advantages to this form of treatment are that the technology is readily available and the required equipment is simple to produce and operate. In addition, there are little or no environmental impacts associated with the use of these forms of radiation, compared to the use of chemical fumigants or sprays. While these treatments show promise, and have been used to eliminate pests on a variety of materials, their effectiveness has not been widely tested at an industrial scale, and cost-effectiveness may be a factor. However, the equipment required to treat sawn wood with gamma radiation has the most important features for commercial success because it is simple to produce and simple to operate (Kunstadt 1998). At

this time, irradiation treatment appears to have the greatest potential for use with high-value forest products that cannot be heat treated or fumigated (Dwinell 2001c).

Gamma irradiation causes cell damage to living organisms with minimal effect on wood properties (Scheffer 1963; Shuler 1971). Gamma rays can penetrate deep into wood, and have been proven capable of killing insects or fungi when the irradiation dose is high enough. Fungi are the most resistant to radiation, requiring significantly higher doses than insects (Kunstadt, 1998). Freitag and Morrell (1998) found that 1.5 Mrad of 60Co appeared to be sufficient for eliminating fungi from pine sawn wood blocks colonized by ***Aspergillus niger*** Tiegh, ***O. piceae*** (Munch) Syd. and P. Syd, ***O. perfectum*** (R.W. Davidson) DeHoog, ***Penicillium*** spp., ***Phlebia subserialis*** (Bound and Galzin) Donk, or ***Postia placenta*** (Fr.) M. Larsen and Lombard.

It has been reported that 99% of the larvae of ***Prionoplus reticularis*** White (Coleoptera: Cerambycidae) in ***Pinus radiata*** D. Don wood were killed by 3677 Gray (Gy) of irradiation after 3 days (Lester et al. 2000). Using gamma irradiation is not a very practical way to conduct phytosanitary treatment for sawn wood on a large-scale due to high operational costs and the effect of high-dose irradiation on wood mechanical properties. A further drawback is that gamma irradiation does not immediately kill organisms, and during post-treatment, phytosanitary inspectors could still find "live" organisms, making it difficult to accept the commodity as safe. Gamma irradiation is a broad spectrum treatment that shows potential as a treatment against a range of organisms, however, its use at an industrial scale on wood products is, as yet, untested.

Electron beam radiation, which is generated by a high-energy electron beam accelerator rather than by decay of radioactive isotopes (as with gamma irradiation), may be an alternative as a wood phytosanitary treatment. Electron beam radiation has been used commercially for sterilizing some agricultural products (Thayer et al. 1996).

4.2.2.8 Biological Control

Another approach is based on inhibition of the sapstain-causing fungi by fungal secondary metabolites produced by plants or microorganisms, for example, the biological control agent massoialactone produced by ***Trichoderma*** spp. fungi, or pine oil derivatives that provided protection of sawn wood from sapstain in laboratory and field trials (Vanneste et al. 2002). Amongst some tested microorganisms, strains of filamentous fungi, ***Trichoderma*** spp. and ***Phlebiopsis gigantea*** (Fr.) Jülich, could control the sapstain fungi on pine wood blocks efficiently (Gradinger et al. 2009). Yang (2009), who summarizes promising potential biological treatments with plant and fungal extracts for wood protection against infestation from some molds, decay fungi, insects, and nematodes, concludes that the current market requirements of wood preservation, low production costs, and long-term efficacy make these types of products unable to compete with existing chemical treatments. In addition, many challenges exist in the registration and commercialization of these products.

4.2.2.9 Summary: Mitigation Treatments for Sawn Wood

Sawn wood is a major global commodity and effective methods to mitigate pests are needed to minimize phytosanitary risk. Ideally, treatments will add to the monetary value of the wood product as well as remove organisms and prevent reinfestation. Debarking wood prior to milling reduces phytosanitary risks and increases wood quality. Kiln drying wood may destroy a broad spectrum of organisms, and at the same time it cures the wood for subsequent use.

In sawn wood, once the bark has been removed and the wood has been treated, the risk of infestation by most organisms of phytosanitary concern is low. As sawn wood is a relatively high-value commodity compared to round wood and wood chips, a greater range of treatments are available. Dielectric heating technologies (MW and RF) may be regarded as promising treatments and practical alternatives for eradication of exotic wood-boring insects, but require further research before they can be considered commercially feasible.

4.2.3 Wood Chips and Pest Mitigation Options

Wood chips are produced on a large scale as raw materials for pulp production, as fuel, or as landscape materials. The end use of the chips is a determinant of the level of phytosanitary risk. Most wood chips traded internationally are used in pulp or paper production and, as such, present a relatively low phytosanitary risk. While wood chips that will be used for landscape or horticultural purposes may represent a phytosanitary risk, wood chips used as biofuels present a lower phytosanitary risk, because pulping and burning will kill potential pests. Some phytosanitary risks may be associated with inappropriate and prolonged storage or transport of infested wood chips. Wood chips used as biofuels or as landscape material comprise minor components of international trade.

Typically, machines that produce wood chips (chippers) have cutting blades mounted on a disc, drum, or cone. Oversized chips are screened out or broken up into smaller pieces. Chips produced for pulp or biofuels can be derived from whole round wood, including bark and branches, lower quality debarked round wood, or milling waste.

While there are possible phytosanitary risks associated with fungi, insects, and nematodes associated with global trade

in wood chips (Magnusson et al. 2001), there are no reported examples of alien pests establishing through this pathway. This may be because the main end uses of wood chips (fuel and pulp) destroy pests during the production of the end products, and because the ability to detect pests established through this pathway is difficult. Although wood chips are small, all chips have the potential to contain fungi and insects, particularly the larger chips. In addition, insects may be accidentally trapped in chips during loading or unloading. This is particularly a risk for forested countries, where the nearness of ports to forests makes it possible for alien invasive species to spread to nearby habitat and become established. There is limited experimental evidence that wood chips might be a pathway for pinewood nematode. Handling wood chips infected by fungi may lead to spread of canker-causing fungal diseases, such as ***Thyronectria austroamericana*** (Speg.) Seeler, the causal agent of Thyronectria canker, and ***F. circinatum*** Nirenberg & O'Donnell, the cause of pitch canker in the forest environment or urban landscape (Koski and Jacobi 2004; McNee et al. 2002). Preventing wood chips (i.e., mulch) originating from symptomatic trees from coming into direct contact with living trees may prevent the introduction of some forest pathogens.

4.2.3.1 Mechanical Screening

The mechanical action of chipping or grinding wood can be effective in destroying wood-dwelling insects. For example, studies have shown that a high percentage of larvae of a range of wood-boring insects are killed by chipping (Wang et al. 2000; McCullough et al. 2004, 2007). More larvae are killed when chips are small (less than 1 inch in size), and when the larvae are relatively large. Insects appear to be killed through physical contact with chipper blades or through extreme forces generated in the chipping process. However, small insects such as some Scolytinae (Coleoptera: Curculionidae) can survive the chipping process (L. Humble and J. Sweeney, Canadian Forest Service, pers. comm.).

The removal of bark prior to chipping reduces phytosanitary risk through destruction of living organisms or disruption of host material so that lifestages cannot be completed (Kliejunas et al. 2001). However, as debarking adds cost to the production process, this step may or may not occur during production of wood chips intended for fuel or landscape purposes.

4.2.3.2 Heat Treatment and Radio Frequency Heating

Combinations and successions of fungi commonly occur during decomposition of wood chips. The ecology of a wood chip pile changes over time as the interior of the pile warms through oxidative processes during decomposition. As the interior of the pile warms, the composition of organisms changes from mesophilic to thermotolerant to thermophilic (Subramanyam1999; Dwinell 2001a). Mesophilic species such as pinewood nematode are primarily found in the outer shell of chip piles, unless the chips are fresh and decomposition has not progressed very far (Dwinell 1997). McCullough et al. (2007) exposed pre-pupae of emerald ash borer (***Agrilus planipennis***) from ash bark chips and ash wood chips in ovens at various temperatures. No pre-pupae survived exposure to 60°C for 120 min, but 17% survived exposure to 55°C for 120 min. These results suggest that this heat treatment may not kill all insects, i.e., some species may be heat tolerant, but these laboratory results have not been extended to operational situations.

Wet heat has been shown to be more effective than dry heat for disinfesting pine chips of pinewood nematode. Immersing chips in hot water for 2 minutes at 55°C is lethal while 10 minutes at 120–135°C is required for lethality when applying dry heat (Kinn 1986).

Dwinell and Carr (1995) studied the effectiveness of radio waves in decontaminating pine chips infested with pinewood nematode. A combination of radio waves and steam destroyed pinewood nematode when wood temperature exceeded 57°C. The advantage of the combined treatment is that high lethal temperatures could be reached sooner by combining steam and radio waves than with either treatment on its own (Dwinell 1997). The use of a combination of radio waves and vacuum has also been shown to be effective as a treatment for wood chips (Dwinell and Carr 1991). The USDA, in co-operation with Pennsylvania State University and FPInnovations in Canada, are currently assisting a large-volume wood chip importer/exporter in the development of a commercial microwave. This apparatus will treat large volumes of wood chips for export to Europe from the United States. The efficacy of this method for pinewood nematode is being assessed (Ron Mack, US Department of Agriculture, pers. comm.).

Although not a heat treatment, extreme cold can also be damaging to organisms. For example, during overwintering, the survival of emerald ash borer pre-pupae was greatly reduced in chip piles compared to intact wood (McCullough et al. 2004).

4.2.3.3 Fumigation

In a study by Leesch et al. (1989), wood chips from several pine species infested with pinewood nematode were successfully fumigated with aluminium phosphide (phosphine) while in transit over a 24-day journey from the US to Sweden. The mortality of pinewood nematode was attributed to high temperature, accumulation of carbon dioxide, and concentration of phosphine. Although this technology has been approved, it has not had a wide commercial use.

4.2.3.4 Liquid Chemical Treatments and Pesticides

Preliminary laboratory studies suggest that chemical treatments can be effective at controlling pests associated with ***Pinus radiata*** wood chips. Morrell et al. (1998) list a number of advantages of using topical fungicides and insecticides in the treatment of wood chips: the surface of the chips can be completely coated; treatment solutions can be adjusted to improve coating or biological efficacy; and the quality of treatment can be monitored by removing samples of chips (unlike heat treatments and fumigants, which do not leave residual evidence of treatment). These topical treatments can be applied as the wood chips are loaded for shipment and provide a viable mitigation treatment for limited periods during shipping.

Treatment with a surface pesticide consisting of the diluted fungicides didecyl dimethyl ammonium chloride (DDAC) and 3-iodo-2-propynyl butylcarbamate (IPBC) and the insecticide chlorpyrifos phosphorothioate is required on ***Pinus radiata*** wood chips exported from Chile to the United States (USDA 2000).

Pinewood nematode can be destroyed in wood chips by immersion in a 0.15% solution of metam sodium (sodium N-methyldithiocarbamate) (Kinn and Springer 1985). Metam sodium's low cost and wide range of control may make it a strong candidate for fumigation on wood chips. However, the use of metam sodium as a dip or fumigant is not considered practical for decontaminating large volumes of pine chips. There are various treatments that are being tested for managing pest risks associated with large-volume wood chip movement, such as the topical insecticide/fungicide Kop-Coat used on ***Pinus radiata*** wood chips being conveyed on or off ships (Ron Mack, USDA, pers. comm.).

4.2.3.5 Irradiation

Irradiation using gamma rays (from cesium-137 or cobalt-60) has proven lethal to pinewood nematode in pine chips at 7–9 kGy (Eicholz et al. 1991; Smith 1991, 1992). However, because pine chips are low in value, the cost of this type of treatment is considered too high to be economically feasible.

4.2.3.6 Biological Control

Vanneste et al. (2002) has demonstrated the ability of some microorganisms to inhibit the growth of sapstain species in laboratory trials on wood chips. Albino strains of ***Ophiostoma*** spp. were used to prevent sapstaining fungi colonization in radiata pine wood chips (Held et al. 2003). ***Ophiostoma piliferum*** (Cartapip 97®) was applied on wood chips to prevent subsequent colonization by sapstain and bluestain fungi (Behrendt et al. 1995). Two fungitoxic compounds identified as trichodermin and trichodermol, isolated from a fungal culture filtrate of ***Stachybotrys cylindrospora*** C.N. Jensen, significantly inhibited the growth of a major bluestain fungus, ***Ophiostoma crassivaginatum*** (H.D. Griffin) T.C. Harrington, on aspen wood chips (Hiratsuka et al. 1994).

4.2.3.7 Summary: Mitigation Treatments for Wood Chips

The mechanical act of chipping wood is, in itself, a treatment against insects. However, this treatment is only effective when larvae are large and chips are small; it is not as effective against small insects, fungi, or nematodes. Similar to round wood and sawn wood, debarking the wood prior to chipping reduces the numbers and types of organisms in the final product.

Treatment with wet or dry heat can be effective in reducing infestation and phytosanitary risk. An important factor in phytosanitary risks associated with wood chips is the temperature of the chip pile. Extremes of heat or cold brought about by weather or natural decomposition processes can be a natural treatment against infestations. However, warm temperatures, such as those found in the holds of ships, can create an ideal environment for some organisms to thrive.

One of the key factors in assessing the effectiveness of treatments for wood chips is cost. As a low-priced commodity, it may not be cost effective to apply some treatments such as irradiation that may be considered more feasible for more valuable commodities.

4.2.4 Plant Parts, Live Propagative Materials, and Pest Mitigation Options

In this section plant parts and live propagative materials refer to those that originate from forest tree species.

Plants for planting[13] represent a pathway for invasive organisms that is consistently cited as high risk, particularly for invasive pathogens (Evans and Oszako 2007). Plants for planting are carriers of pests, which could be associated with stem (wood and/or bark), branches, foliage, fruits/cones, roots, and sometimes soil or growing media.

The North American Plant Protection Organization (NAPPO) has developed two standards for plants for planting. The first one addresses requirements for system approaches to control the movement of pests on nursery stock based on pest guilds[14] (NAPPO 2005), and the second one provides guidance for screening such plants prior to import (NAPPO 2008). An IPPC Expert Working Group for Plants for Planting is reviewing potential options for regulating plants for planting internationally and is developing an ISPM to provide guidelines on the management of pest risks associated with the international trade of plants for planting.

13 Defined as plants intended to remain planted, to be planted or replanted (ISPM 5, FAO 2010).

Spread of some forest tree diseases and invasive alien species (e.g., chestnut blight, white pine blister rust, hemlock woolly adelgid, balsam woolly adelgid) has resulted from the accidental importation, propagation, and planting of infested plants, plant parts, or nursery stock. Infested plant propagative material is often asymptomatic when it is shipped and planted, and results in rapid and widespread outbreaks of alien invasive species (Ostry 2001). Bonsai plants, potted Christmas trees, and large trees for planting present higher risks; a variety of pests may move with them including aphids, scale insects, adelgids, bark beetles, weevils, moths, and foliar, as well as canker and root rot fungi. The potential pest hazard associated with non-manufactured forest products, such as Christmas trees or cones, includes all forest pest types. Christmas trees are a widely used commodity and are often grown as a monoculture, increasing the potential for pest outbreaks and spread of pests. Therefore, these products should be considered a great risk when traded internationally (Ormsby 2001).

Importing countries generally develop a pest risk analysis that helps identify pests of concern and aids in the development of specific import requirements. Requirements can include surveillance, pest-specific surveys, identification of pest-free areas, treatments, pre-shipment inspections, and post-entry quarantine. Additional opportunities for inspection for pests could occur during handling of plants for planting (including pruning, harvest, and packaging) by appropriately trained personnel.

There is not enough information to fully understand this pathway. There is also a paucity of research on treatments to reduce phytosanitary risks in plant parts and live propagative material.

4.2.5 Seeds and Pest Mitigation Options

Seeds[15] from forest tree species as pathways for the movement of quarantine pests have not been well documented. However, the IPPC has established a work item to consider the risks of forest tree seed moving in international trade.

In forest ecosystems, an increasing phytosanitary risk is associated with international and inter-regional exchanges of seeds for plantation and/or the establishment of seed orchards (Roques and Skrzypczynska 2003). Insects, mites, and fungi developing within or on seeds are of concern because of the high volume of seeds of both conifers and broadleaved species that are traded (Roques 2001). Despite these risks, there is no systematic control on the movement of seed lots.

More than 400 species of phytophagous insects and mites are known to exploit seed cones of world conifers (Turgeon et al. 1994). However, only the species spending their entire development (egg to pupa) as endophytes within seeds constitute a real threat of invasion. Seeds can harbour a wide variety of immature stages of insects. The majority of seed insects belong to the following five orders: Coleoptera (beetles), Hemiptera (plant bugs), Lepidoptera (moths and butterflies), Diptera (flies), and Hymenoptera (seed chalcids). The genus ***Megastigmus*** (Torymidae) from the Hymenoptera order is the largest group of forest seed insects. A total of 21 species of ***Megastigmus*** seed chalcids are recognized in Europe, North Africa, and Asia Minor, of which 15 species develop in seeds of conifers, while six infest the seeds of Angiosperms. Thirteen of these chalcid species are considered to be native, whereas the other species were introduced from North America (seven species) and South Africa (one species) through seed trade (Roques and Skrzypczynska 2003). For example, the Douglas-fir seed chalcid, ***Megastigmus spermotrophus*** (Wachtl), which was introduced from North America, is recorded all over Europe, wherever exotic trees of the genus ***Pseudotsuga*** have been planted, becoming Europe's most important pest in fir seed orchards. Similarly, the range of three North American chalcids attacking ***Abies*** seeds (***M. milleri*** [Milliron], ***M. pinus*** [Parfitt] and ***M. rafni*** [Hoffmeyer]) now covers all of western Europe and a large part of central Europe (Roques and Skrzypczynska 2003). According to Roques et al. (2003), in China, a total of 39 insect species, primarily seed chalcids in the genus ***Megastigmus*** (Hymenoptera), but also midges (Diptera: Cecidomyiidae), are listed as potential seed-borne invaders of Chinese conifers. Uncontrolled importation of seeds and nuts of broadleaved trees could facilitate the introduction of seed chalcids, seed bruchids, tortricid moths, and nut weevils into China. Of the 72 chalcid species known to attack broadleaved seeds over the world, only six species are present in China.

Seeds can also carry saprophytic or pathogenic fungi. Seed-borne fungi include all fungal types contaminating the surface of the seed or infecting its tissue. Seed-transmitted fungi may not necessarily cause disease symptoms on the seed itself, but only produce disease on seedlings in the nursery or in the field (Neergaard 1979). An example of a seed-transmitted disease is "damping off," a common nursery disease caused by the fungal genera ***Fusarium***, ***Phytophthora***, ***Rhizoctonia***, and ***Phythium***. The disease usually originates from nursery soil, but is occasionally introduced via infected seeds (Gardner 1980; Ivory and Spreight 1993). In three ***Araucaria*** species in Australia, seed-borne ***Rhizoctonia solani*** Kühn proved to be the principal cause of damping off (Kamara et al. 1981).

14 A group of species that use the same ecological resource in a similar way and therefore sharing a similar ecological niche.

15 Seeds, as a commodity class in this document, refer to seeds intended for planting and not for consumption or processing (ISPM No.5, FAO 2010).

Most fungi infecting fruits and seeds in the field require relatively high humidity for germination and growth, and become inactive at moisture contents below approximately 25%. Typical genera of field fungi include ***Fusarium, Botrytis, Ciboria, Sclerotina, Phomopsis, Valsa,*** and ***Gloesporium*** (Bonner et al. 1994). Another group of fungi, known as storage fungi, commonly called moulds, are facultative saprophytes living on moist dead organic materials. Storage fungi frequently occur when seed moisture cannot be brought below a safe level, generally around 10%. Most storage fungi attacking orthodox seeds[16] belong to the genera ***Aspergillus, Penicillium, Rhizopus, Chaetomium,*** and ***Mucor*** (Schmidt 2000). In India, ***Aspergillus niger*** Tiegh. is a frequent storage fungus attacking seeds of the sal tree, ***Shorea robusta*** Gaertn. f. This fungus can develop at a seed moisture content at or above 12%, and its attack becomes increasingly worse at higher humidity and seed moisture content (Singh et al. 1979). In the Philippines, Dayan (1986) found 17 fungal species associated with orthodox seeds. Mohanan and Sharma (1991) have listed seed-borne fungi for a number of indigenous and exotic trees in India. An extensive worldwide list of microorganisms associated with tree seeds is summarized by Mittal et al. (1990). It should be noted that recalcitrant seeds[17], which are stored at high moisture content, may continue to support fungi usually active only under field conditions. For example, Mycock and Berjak (1990) found that ***Fusarium*** sp., a typical field fungus, became dominant during storage in four recalcitrant species.

According to Fraedrich (2001), there are several notable pathogens of conifers that are seed-borne and could have severe economic and ecological consequences if they are introduced and become established in regions where they are not native. These pathogens include ***Sphaeropsis sapinea*** (Fr.) Dyko & B. Sutton, ***Sirococcus conigenus*** (DC.) P.F. Cannon & Minter, and ***Fusarium circinatum*** Nirenberg & O'Donnell. ***Sirococcus sapinea*** causes a blight of pines and has been particularly devastating in countries that grow pine trees as exotics (Currie and Toes 1978; Smith et al. 2000). Repeated introductions of pine seed infected with ***S. sapinea*** may explain the high genetic diversity of this pathogen in South Africa (Wingfield et al. 2001). Seed transmission may also explain the presence of this fungus in Europe in pine plantations (Desprez-Loustau 2009). ***Sirococcus conigenus*** causes a shoot blight in a wide range of conifer hosts in North America, Europe, and Asia (Sutherland 1987; Smith et al. 2003; Sinclair and Lyon 2005). This blight can affect trees at all ages (Ostry et al. 1990; Halmschlager et al. 2000; Anglberger and Halmschlager 2003), and has caused severe problems in nurseries that have been traced to seed lots with seeds infected by ***S. conigenus*** (Sutherland 1987; Butin 1995). Pitch canker, caused by ***Fusarium circinatum,*** is a disease that has affected nurseries, and native and exotic pine plantations in South Africa, Japan, Chile, Spain, and Mexico (Dwinell et al. 1985; Dwinell and Fraedrich 2000). Other ***Fusarium*** spp. are regularly isolated from conifer seeds and are recognized as pathogens in forestry nurseries in many parts of the world (Bloomberg 1981; James 1985; James et al. 1991).

Factors affecting the degree of infection of seeds include the stage of maturation at the time of collection and whether the seeds had contact with the ground (rather than being tree picked) (Fraedrich 2001). Most seed-borne pathogens may remain at low levels and harmless if their conditions for growth and development are controlled. For this reason, seed processing should take place as soon as possible after collection, and seeds should subsequently be stored under conditions unfavourable to further development, i.e., low temperature and low moisture content.

Properly established quarantine controls in countries that import tree seeds can restrict the spread of exotic seed-borne tree pathogens (Burgess and Wingfield 2002; Durán et al. 2008).

Some insects can be detected in seeds. For example, X-ray techniques can detect infested conifer seeds amongst healthy ones, but are rarely used in the trade of seeds. The main treatments used for seeds—thermal or chemical treatment—balance reductions in phytosanitary risk against reducing seed viability. Although the complete elimination of seed-borne inoculum is desirable, in practice, seed treatments often do not provide this level of control.

4.2.5.1 Thermal Seed Treatment

Heat treatment, using various methods such as hot water, hot air, solar heat, aerated steam, and irradiation have been used to control the spread of seed-borne pathogens while maintaining seed viability. An advantage of thermal treatment is that seeds can be planted without chemical residue. Serotinous cones, which are conifer seed cones that must be exposed to high temperatures to release the seeds during extraction procedures, may be partially insect-free after

16 Seeds that acquire desiccation tolerance during development, and can be successfully dried to moisture contents as low as 5% without injury and are able to tolerate freezing temperatures (Roberts 1973).

17 Seeds that undergo little, or no, maturation drying below 30 % without injury, remain desiccation sensitive both during development and after they are shed, and are unable to tolerate freezing temperatures (Roberts 1973).

processing. Ruth and Hedlin (1974) found that larvae of the chalcid ***M. spermotrophus*** in ***Pseudotsuga menziesii*** (Mirbel) Franco seeds were killed when treated at 45°C for 27 hrs (2-year-old seed) and for 33 hrs (1-year-old seed). These heat treatments did not affect rate of germination or seedling growth when applied to uninfested seed. Heat treatment can be used in tree species where seeds are tolerant to these high temperature exposures, i.e., orthodox seeds (Schmidt 2000). Low temperatures may also be effective in killing seed insects. For example, in Argentina, a cold treatment of -18°C for 10 days effectively killed all stages of bruchids (Coleoptera: Bruchidae) in infested seeds of ***Prosopis chilensis*** (Mol.) Stuntz (Mazzuferi et al. 1991). Some attempts have also been made to use hot water treatments to control pathogens in tree seeds. For example, a 2–2.5 hour submersion of ***Quercus petraea*** (Matt.) Liebl. seeds in water at 40–45°C is used to control fungal infection of ***Ciboria batschiana*** (Zopf) Buchwald (Delatour 1978). However, brief exposures to high temperature applied by dry air or submersion in hot water are only effective when the fungus is heat sensitive and the seed heat tolerant (Agarwal and Sinclair 1997). These methods have not been as successful as chemical control, since fungicides may be more practical than heat for destroying internal pathogens (Fraedrich 2001). Furthermore, heat treatment may leave the seed coat more vulnerable to invasion by other pathogenic fungi (Kehr and Schröder 1996).

Dielectric heating (MW and RF) has been used successfully for thermal treatment in agricultural seeds, but has not yet been tested with tree seeds. For example, MW radiation has been successful in destroying blight ***Fusarium culmorum*** (Smith) Saccardo during research trials in wheat seeds (Von Hoersten and Luecke 2001). The application of RF technology by Cwiklinski and Von Horsten (1999) has successfully eradicated ***F. culmorum*** from wheat seeds while maintaining germination potential. These authors reported complete eradication of the fungus on wheat seeds at temperatures of 70–75°C, and treatment times of 150–180 s, when the initial seed moisture content was 15%.

4.2.5.2 Chemical Seed Treatments

Fungicides have been used routinely to control seed-borne pathogens and are often the cheapest and most effective means of control. Fungicides are used to kill or to inhibit growth of seed-borne fungi and can be systemic or non-systemic in their action. Some fungicides are only effective if they are in direct contact with the fungi. If the fungus is already present deep within the seed, it may escape treatment (Gardner 1980); thus, highly selective systemic fungicides have proved to be the most effective for the eradication of deep-seated seed-borne fungi in tree seeds (Mohanan and Sharma 1991). According to Fraedrich (1996), disinfectants such as sodium hypochlorite and hydrogen peroxide have proved useful for reducing contamination of ***F. circinatum*** associated with the seed coats of some conifer species, such as shortleaf (***Pinus echinata*** Milll), longleaf, (***P. palustris*** Mill), and Monterey (***P. radiata***) pine seeds. Fungi on ***Abies amabilis*** seeds were also reduced by surface sterilization using hydrogen peroxide, without affecting germination capacity (Edwards and Sutherland 1979).

There is variation in the effectiveness of different fumigants and fungicides to control certain fungal pathogens. For example, the best control of the fungus ***Waitea circinata*** Warcup & Talbot in ***Pinus resinosa*** Aiton seeds was obtained with the fumigants propylene oxide, metam sodium, and chloropicirin, and with the fungicides tetramethylthiuram disulfide and ethyl mercaptan (Agnihotri 1971). The relative efficacy of five commonly used fungicides was tested on eight common storage fungi on seeds of three different tree species in India. One of the fungicides, copper oxychloride, had no effect on ***Aspergillus niger*** van Tieghem, and the effect of tetramethylthiuram disulfide depended on tree species (Purohit et al. 1996). Several fumigants that have been effective to control insects on seeds are available. The most common ones are MeBr, a mixture of carbon disulphide and carbon tetrachloride, and phosphine (Willan 1993). No larvae of six species of ***Megastigmus*** or three species of ***Cecidomyiidae*** survived fumigation when a mixture of carbon disulfide and carbon tetrachloride was applied. However, these same species were tolerant to MeBr treatment (Roth and Strasser 1971). Better results were obtained with a fumigation treatment of ***Araucaria angustifolia*** (Bertol.) Kuntze seeds against attack by ***Cydia (Laspeyresia) araucariae*** (Pastrana) using carbon disulfide than with MeBr (Grodzki 1972). Fumigation of ***Cryptomeria japonica*** (Thunberg ex Linnaeus f.) D. Don seeds with aluminium phosphide (phosphine) was an effective control against the seed chalcid ***Megastigmus cryptomeriae*** Yano (Xu et al. 1989). Smith and Ueckert (1974) used Cythion to control seed insects in ***Prosopis glandulosa*** Torrey. Warm water (30–40°C) and fumigation have been used to treat ***Eurytoma laricis*** Yano (Hymenoptera: Eurytomidae), an insect in larch seeds, which is under quarantine regulations in China and affects ***Larix kaempferi*** (Lambert) Carriére, ***Larix gmelinii*** (Rupr.) Kuzen, and ***Larix gmelinii*** var. ***principis-rupprechtii*** (Mayr) Pilger (Gao et al. 1983).

Some fumigants have been used to test seed viability. For example, ***Pinus sylvestris*** Linnaeus, ***Pinus mugo*** subsp. ***mugo*** Turra, ***Picea abies*** (Linnaeus) Karsten, and ***P. glauca*** (Moench) Voss seeds were fumigated with standard dosages of MeBr. Results indicated that seeds need to have a low moisture content to survive (Jones and Havel 1968). HCN was used to treat ***Pinus kesiya*** Royle ex Gordon and ***Pinus merkusii*** Junghuhn and de Vriese seeds without significant reduction in germination (Lasmarias and Baja-Lapis 1977).

Since some effective fungicides are being withdrawn from the market in countries such as Denmark, Knudsen et al. (2004) tested several biological control agents. These authors have found that ***Clonostachys rosea*** (Link: Fr.) Schroers, Samuels, Siefert, and W. Gams (strain IK726) significantly reduced the growth of seed-borne fungi in acorns of English oak (***Quercus robur*** L.) when combined with a hot water treatment.

Scientists in India have used extracts of plants, oils, ashes, and minerals for the control of seed insects (Golob and Webley 1980). However, the efficacy of these compounds on tree seeds needs to be proven.

4.2.5.3 Summary: Mitigation Treatments for Plant Parts, Live Propagative Materials, and Seeds

A phytosanitary standard for plant parts and live propagative materials has been proposed. Currently, individual countries carry out an inspection and certification when needed for individual pests of concern. Both plants for planting and seeds represent a very unique and significant phytosanitary risk, since living pests of phytosanitary concern could be introduced directly into the forest with planting of seedlings or sowing of seed. At present, there are limited phytosanitary requirements for the international movement of forest tree seed; the IPPC is developing a standard to address this need.

5. Concluding Remarks

Global trade in forest products has been expanding over past decades both in volume and value. This increased global movement of forest products has made many countries more vulnerable to the introduction of alien forest invasive species, and consequent ecological and economic impacts. On the other hand, the increased phytosanitary risks originating from these alien species, in turn, have had an impact on the trade of forest products in some countries.

Pests are reduced as wood moves through various processes from round wood to finished products. Phytosanitary risks are also decreased through available treatments. Given the range of potential forest invasive species types, and the variety of forest product commodities, some mitigation treatments are more effective than others. Operational practicalities must be taken into account, for example, the requirements for treating round wood are very different from those required by sawn wood and wood chips. Cost is also a factor, since fewer options for cost-effective treatments are available for lower-valued commodities (i.e., wood chips).

An international standard for wood commodities is currently being developed by the IPPC. The implementation of import regulations, systems for compliance, surveillance, reporting, control, and export certification will be very helpful for mitigating phytosanitary risks from wood. This is particularly critical for untreated round wood, which constitutes one of the most important forestry commodities in international trade, and is a major source of forest pests and diseases. Strategies for understanding phytosanitary risks and developing meaningful mitigation treatments are slowly improving. Heat treatment and treatment with radio-frequency and microwave radiation are effective, safe, and economical alternatives to MeBr fumigation for phytosanitary treatment of wood.

Another pathway with high phytosanitary risks is living material—plants for planting and seeds. The plants for planting pathway requires attention. However, there is a lack of research on the frequency, importance, and risks of pests on this pathway. The application of treatments to remove alien pests from this pathway is more difficult than with other pathways in forestry. There are no international or regional phytosanitary standards for the movement of forestry seeds, and most work on mitigation treatments has been done in agricultural seeds.

Countries across the world are becoming aware of the danger of the unintentional entry of forest alien species through the global movement of forest products. There is a need for co-ordinated international action aimed at preventing the spread of forest alien species, through improved surveillance, diagnostic methods for interception, and mitigation treatments. We need to focus on improving methods of prevention and mitigation. Unfortunately, many underdeveloped or developing countries lack the resources for these services to operate effectively. As in the case of infectious and communicable diseases, the notion of the vulnerability of "the weakest link in the chain" also applies to forest alien species, where the country with the least available quarantine resources may determine the risks for the entire region. The inability of a country to implement acceptable quarantine services is ultimately a matter of global concern, not exclusively a matter of national interest. Therefore, an argument can be made for global co-ordination to limit the spread of forest alien pests.

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